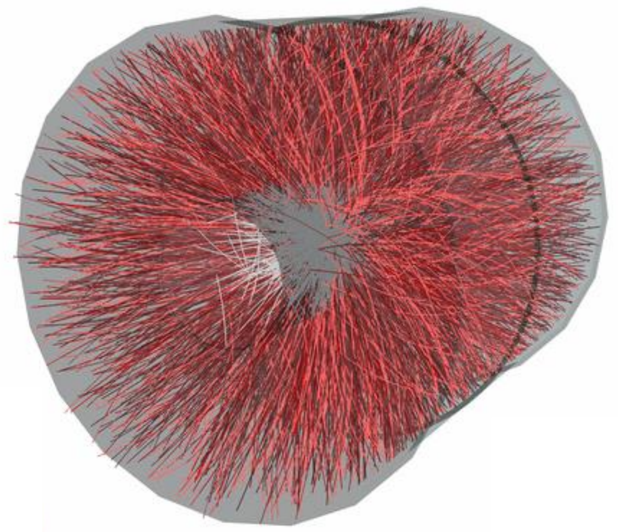
Physics with relativistic heavy-ion collisions

(ALICE, ATLAS, CMS, HADES, LHCb, PHENIX, STAR)



ISVHECRI 2014

19.08.2014

Benjamin Dönigus

Institut für Kernphysik

Goethe Universität Frankfurt

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

IKF Institut für Kernphysik Frankfurt

Content

- **Collectivity and approach to equilibrium**
- **High p_T and jets**
- **Heavy flavour and electroweak bosons**
- **Search for exotic objects**

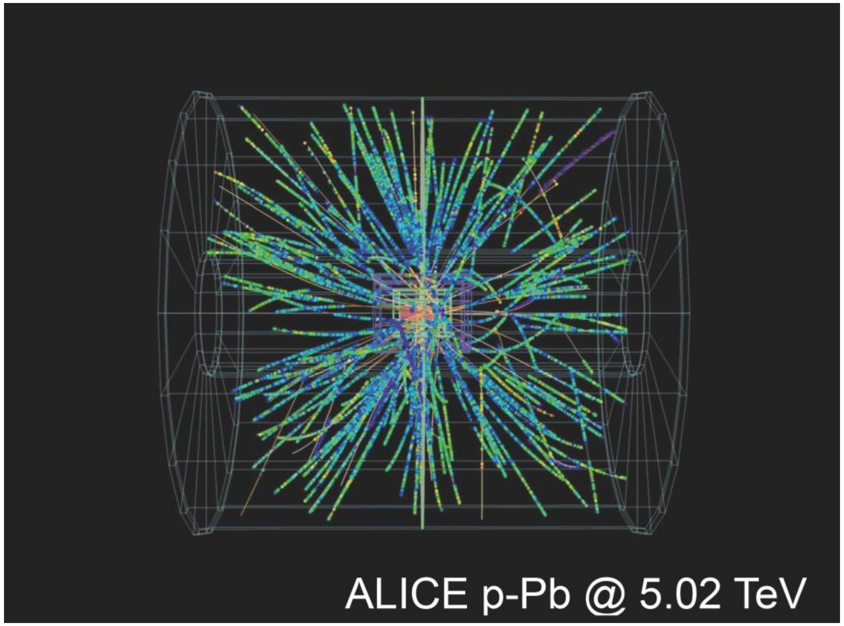
AA and pA/dA

- Trying to summarise the physics done in the relativistic heavy-ion community in a talk of 30 minutes itself seems difficult
- Choosing mainly topics of the field which might be interesting for the high-energy cosmic ray community is still quite challenging

→ Mainly focus here on recent results in p-Pb/d-Au collisions since it seems to have the largest overlap with the heavy-ion and the high-energy cosmic ray communities

Why do we investigate p-Pb collisions?

- Traditional idea: reference for Pb-Pb collisions in order to investigate *cold nuclear matter (initial state) effects*.
- However, the data turned out to be very interesting in itself:
  - Do we observe *collective effects* in a small system such as p-Pb collisions? Is there *hot matter* in local thermal equilibrium created?
  - Do we observe an *enhancement* of high-p_T particles with respect to pp collisions while we see a *suppression* in Pb-Pb collisions?
  - What can we learn from heavy flavour and electroweak bosons?



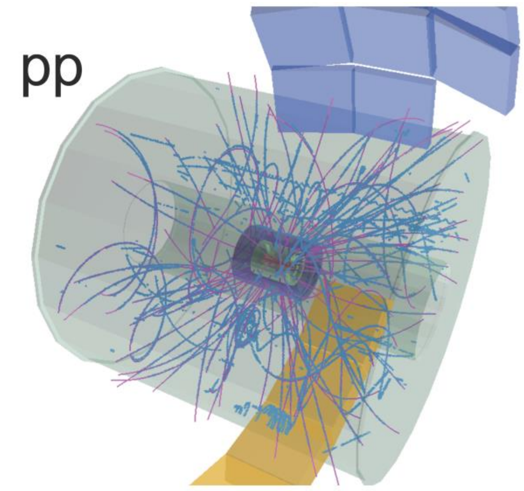
Collectivity and approach to equilibrium

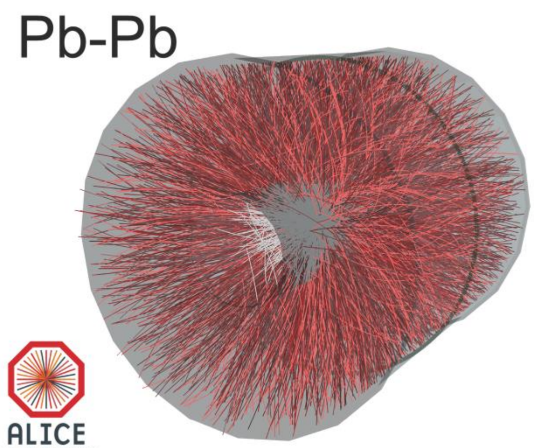
Introduction — collectivity

- It is important to distinguish between
  - a *system of individual particles* and
  - a *medium* in which individual degrees of freedom do not matter anymore and we can apply thermodynamic concepts.

- Thermodynamic concepts are typically used for systems with large number of particles (> 10^4) particles in *local thermal equilibrium*.
  - central (0-5%) Pb-Pb collisions (LHC): $dN_{ch}/d\eta \approx 1600$
  - high mult. (0-5%) p-Pb collisions (LHC): $dN_{ch}/d\eta \approx 45$
  - min. bias pp collisions (LHC): $dN_{ch}/d\eta \approx 6$

- Lifetime of the system must be long enough and mean free path must be short enough so that equilibrium can be established by several (simulations indicate about 3-6) interactions between its constituents.



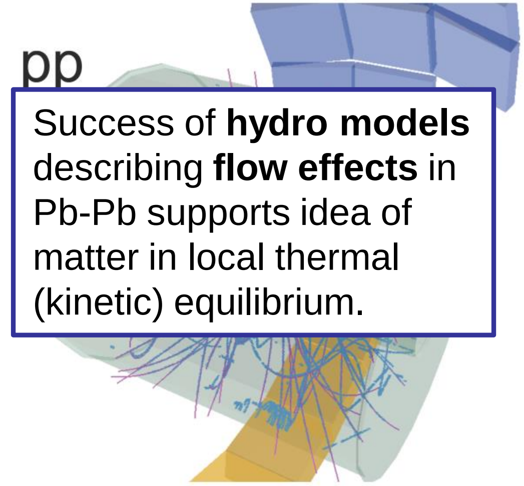


Introduction — collectivity

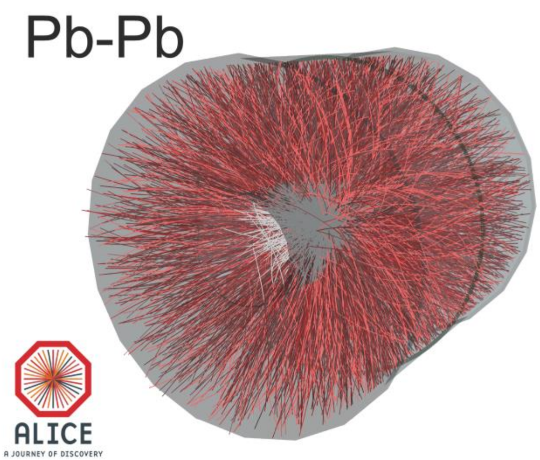
- It is important to distinguish between
  - a *system of individual particles* and
  - a *medium* in which individual degrees of freedom do not matter anymore and we can apply thermodynamic concepts.

- Thermodynamic concepts are typically used for systems with large number of particles (> 10^4) particles in *local thermal equilibrium*.
  - central (0-5%) Pb-Pb collisions (LHC): $dN_{ch}/d\eta \approx 1600$
  - high mult. (0-5%) p-Pb collisions (LHC): $dN_{ch}/d\eta \approx 45$
  - min. bias pp collisions (LHC): $dN_{ch}/d\eta \approx 6$

- Lifetime of the system must be long enough and mean free path must be short enough so that equilibrium can be established by several (simulations indicate about 3-6) interactions between its constituents.



Success of **hydro models** describing **flow effects** in Pb-Pb supports idea of matter in local thermal (kinetic) equilibrium.

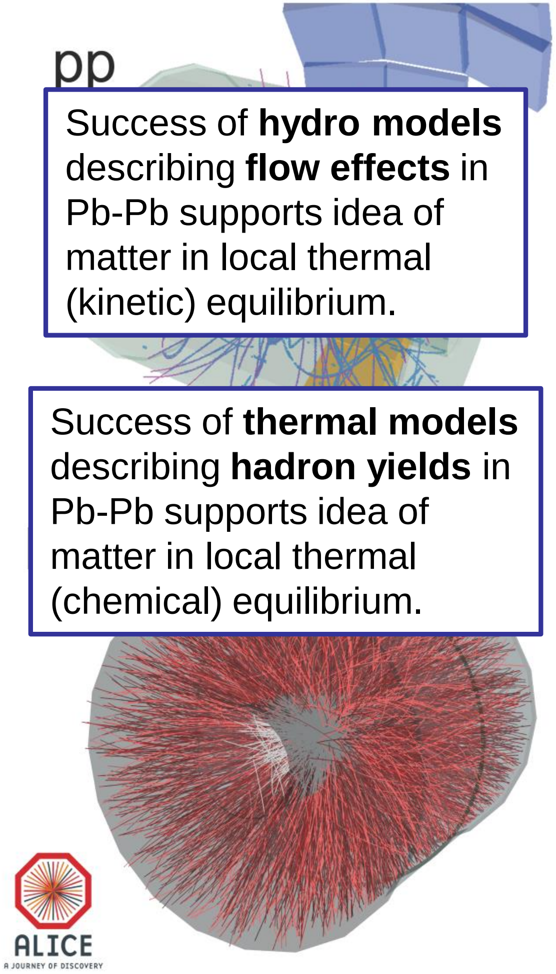


Introduction — collectivity

- It is important to distinguish between
  - a *system of individual particles* and
  - a *medium* in which individual degrees of freedom do not matter anymore and we can apply thermodynamic concepts.

- Thermodynamic concepts are typically used for systems with large number of particles (> 10^4) particles in *local thermal equilibrium*.
  - central (0-5%) Pb-Pb collisions (LHC): $dN_{ch}/d\eta \approx 1600$
  - high mult. (0-5%) p-Pb collisions (LHC): $dN_{ch}/d\eta \approx 45$
  - min. bias pp collisions (LHC): $dN_{ch}/d\eta \approx 6$

- Lifetime of the system must be long enough and mean free path must be short enough so that equilibrium can be established by several (simulations indicate about 3-6) interactions between its constituents.

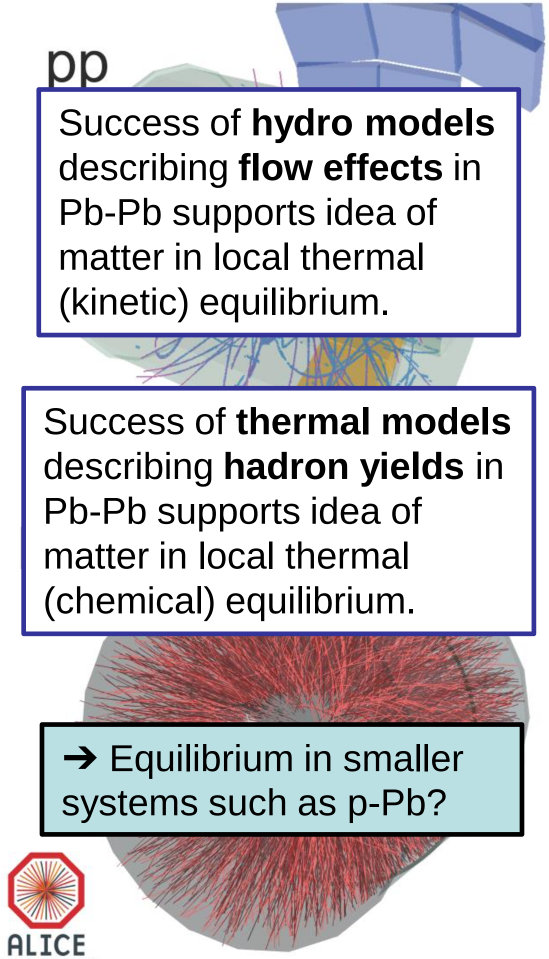


Introduction — collectivity

- It is important to distinguish between
  - a *system of individual particles* and
  - a *medium* in which individual degrees of freedom do not matter anymore and we can apply thermodynamic concepts.

- Thermodynamic concepts are typically used for systems with large number of particles (> 10^4) particles in *local thermal equilibrium*.
  - central (0-5%) Pb-Pb collisions (LHC): $dN_{ch}/d\eta \approx 1600$
  - high mult. (0-5%) p-Pb collisions (LHC): $dN_{ch}/d\eta \approx 45$
  - min. bias pp collisions (LHC): $dN_{ch}/d\eta \approx 6$

- Lifetime of the system must be long enough and mean free path must be short enough so that equilibrium can be established by several (simulations indicate about 3-6) interactions between its constituents.



Success of **hydro models** describing **flow effects** in Pb-Pb supports idea of matter in local thermal (kinetic) equilibrium.

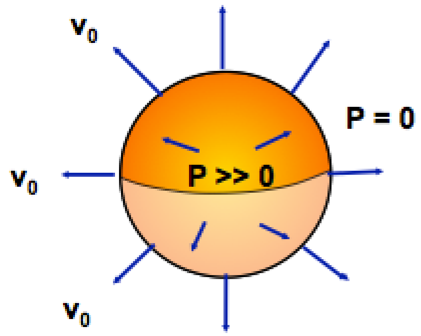
Success of **thermal models** describing **hadron yields** in Pb-Pb supports idea of matter in local thermal (chemical) equilibrium.

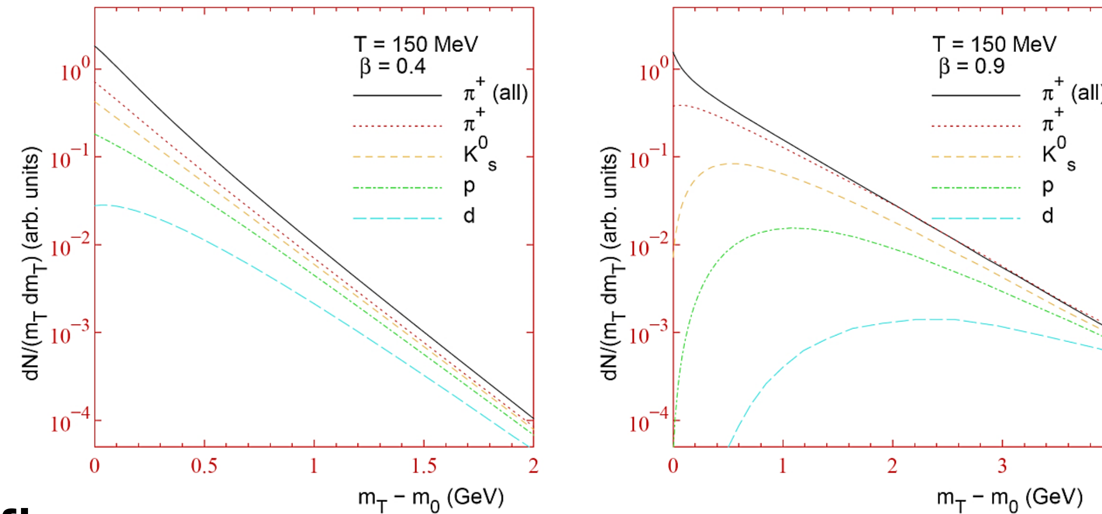
➔ Equilibrium in smaller systems such as p-Pb?

ALICE
A JOURNEY OF DISCOVERY

Radial and elliptic flow

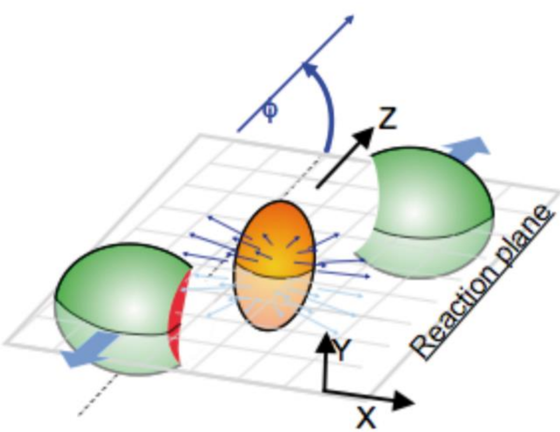
Isotropic (radial) flow

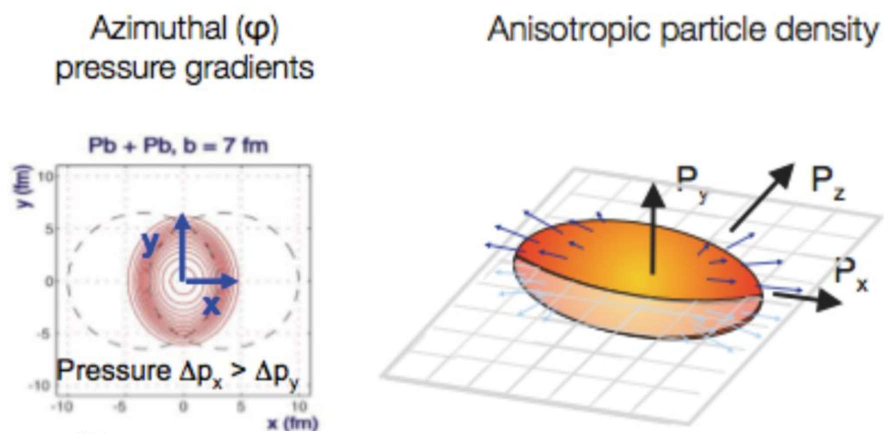




Anisotropic (elliptic) flow

[hep-ph/0407360]

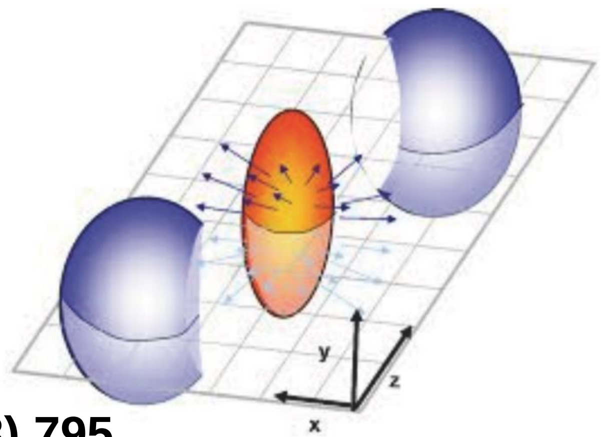




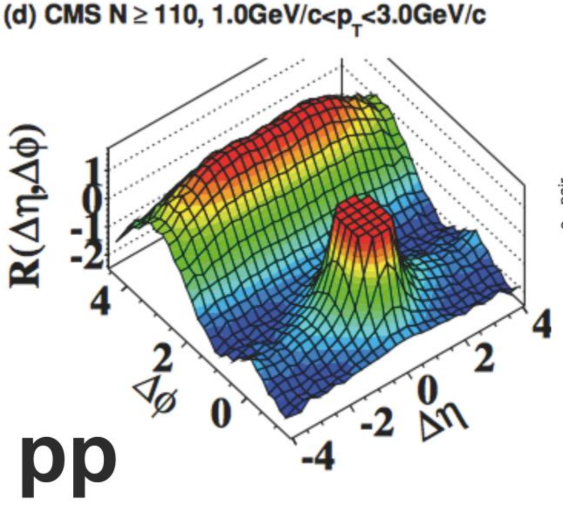
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + ..$$

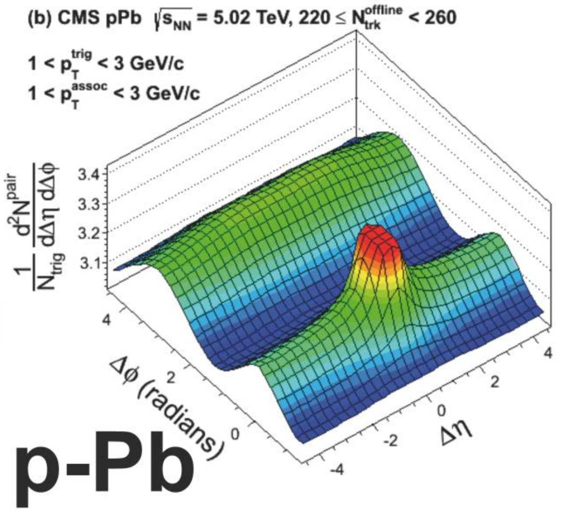
Angular correlations and double ridge (1)

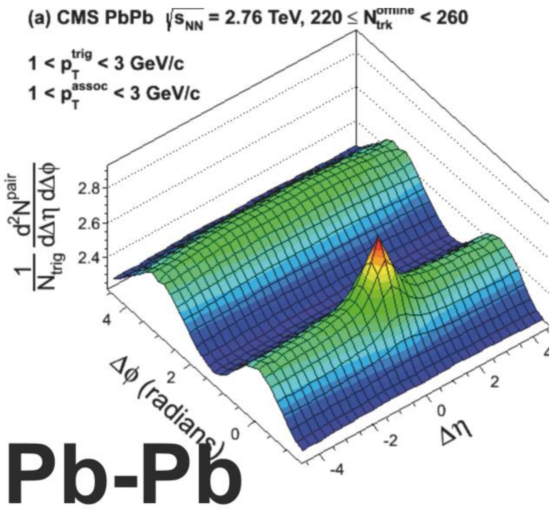
- Di-hadron correlations study anisotropies in the particle production on event-by-event basis.
- In Pb-Pb collisions, they are associated with elliptic flow resulting from the hydrodynamical expansion of the system and the initial collision geometry.



JHEP 1009:091,2010 **Phys. Lett. B 718 (2013) 795**

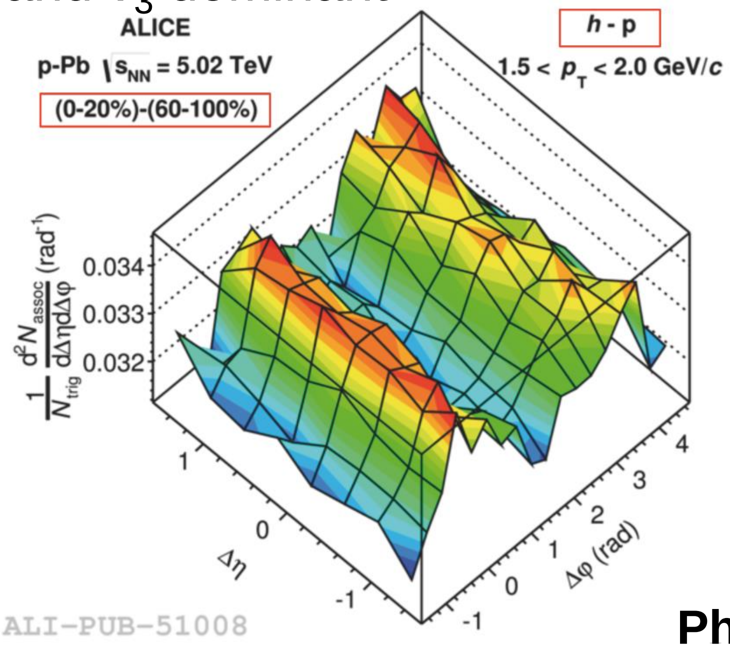


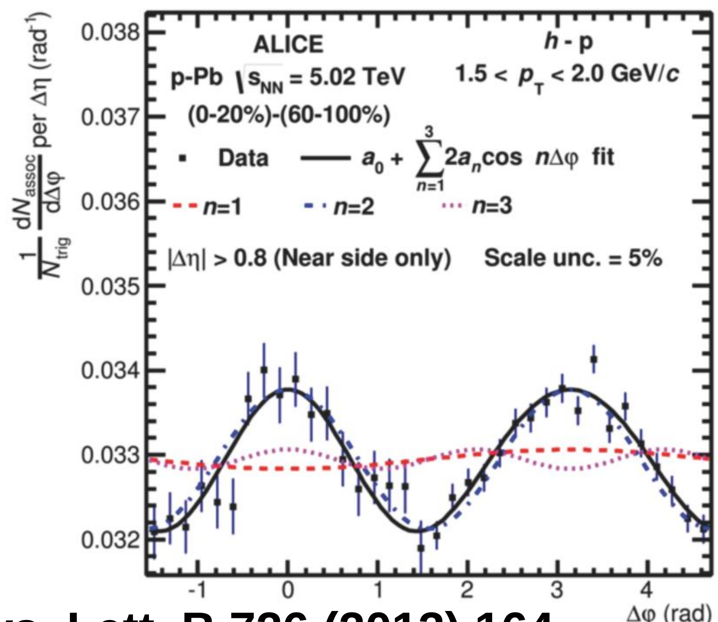




Angular correlations and double ridge (2)

- Triggered further measurements from ATLAS, CMS, ALICE…
- From the high-multiplicity yield subtract the jet yield obtained in low-multiplicity events (no ridge) → double ridge.
- Correlations of non-identified and also identified particles.
- Azimuthal projection is decomposed into Fourier components: v_2 and v_3 dominant



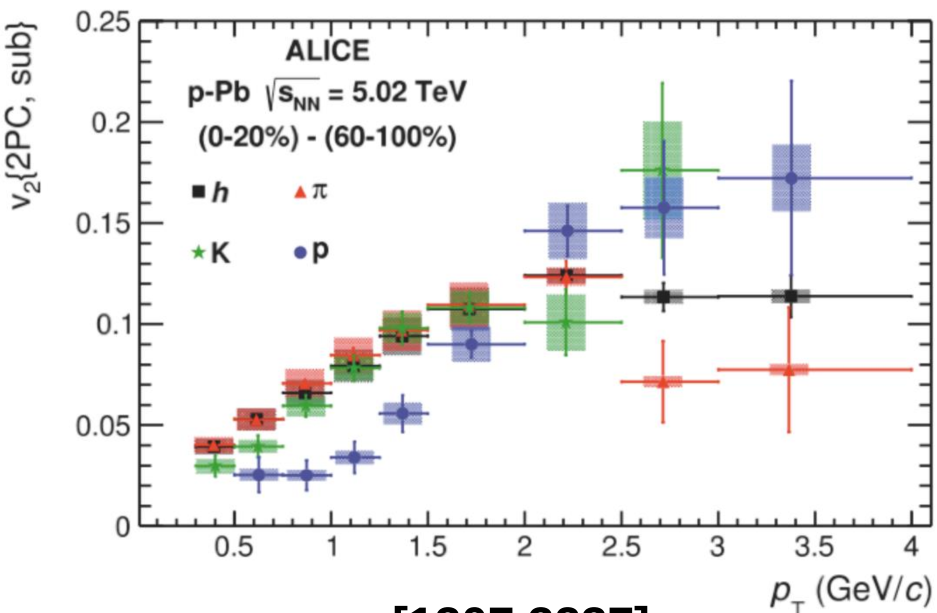


Phys. Lett. B 726 (2013) 164

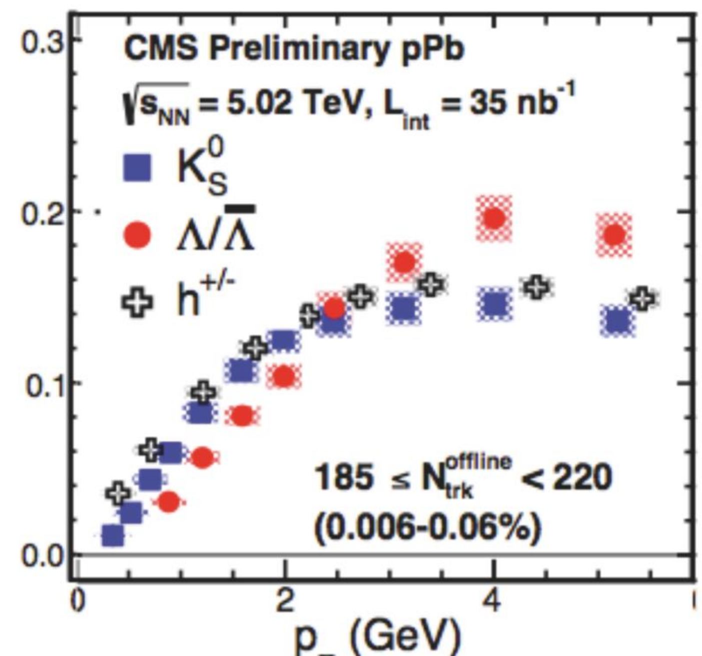
Angular correlations and double ridge (3)

- Mass ordering observed by ALICE and CMS → reminiscent of Pb-Pb phenomenology
- as expected from hydrodynamic behavior: $p = \beta\gamma \cdot m$

[CMS-HIN-14-002]



[1307.3237]

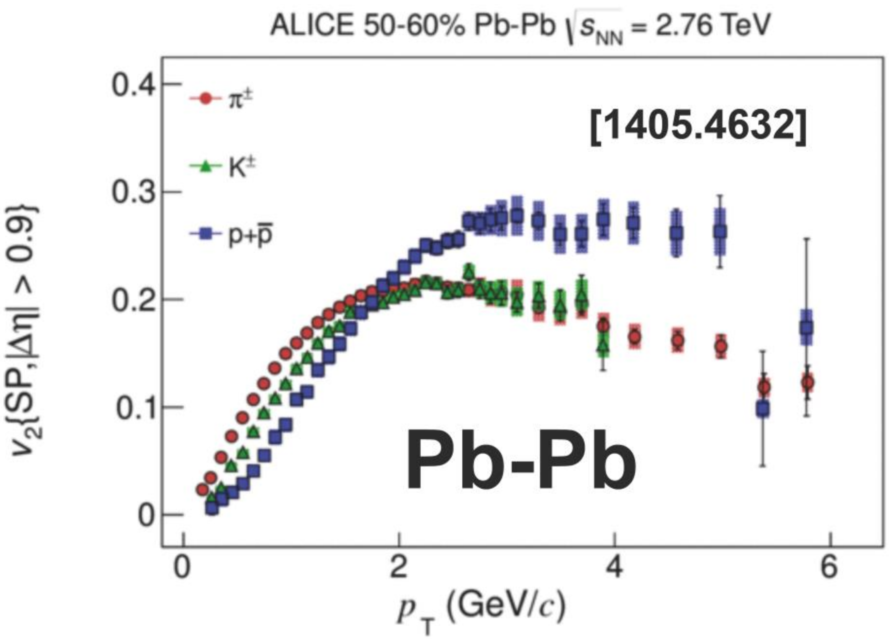


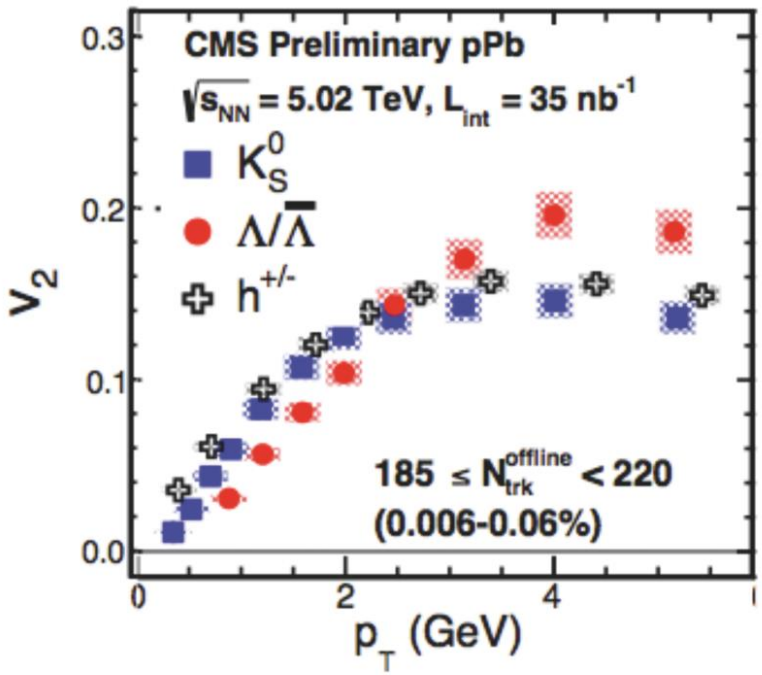
CMS: no subtraction of peripheral events!

Angular correlations and double ridge (3)

- Mass ordering observed by ALICE and CMS → reminiscent of Pb-Pb phenomenology
- as expected from hydrodynamic behavior: $p = \beta\gamma \cdot m$

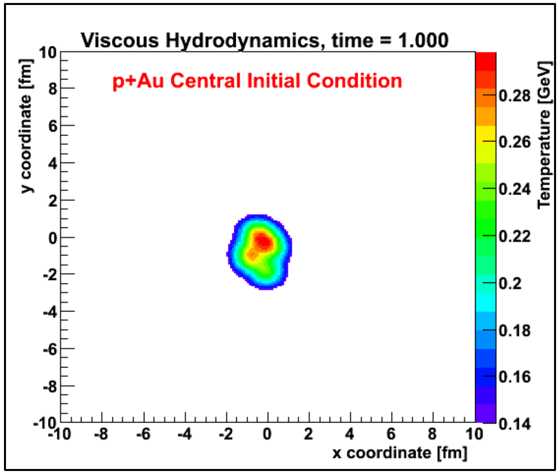
[CMS-HIN-14-002]

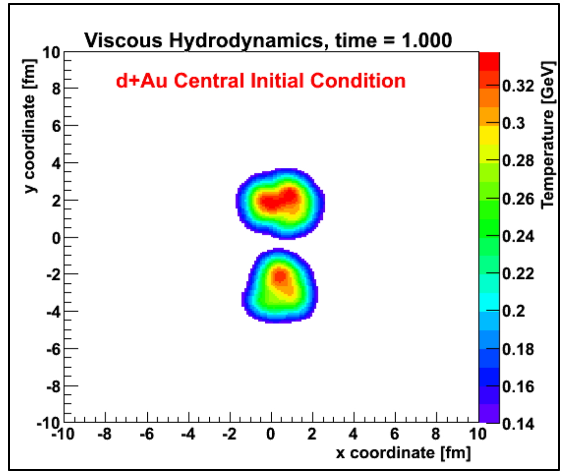


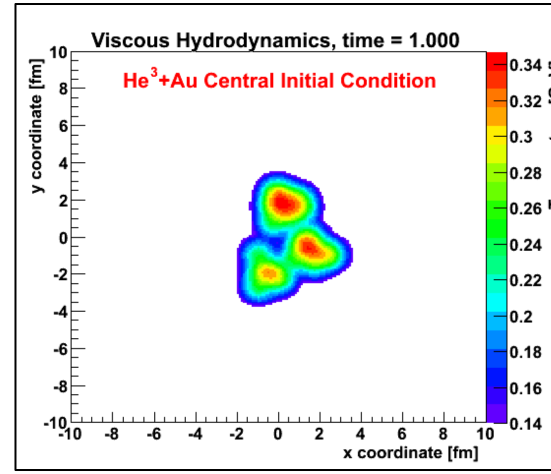


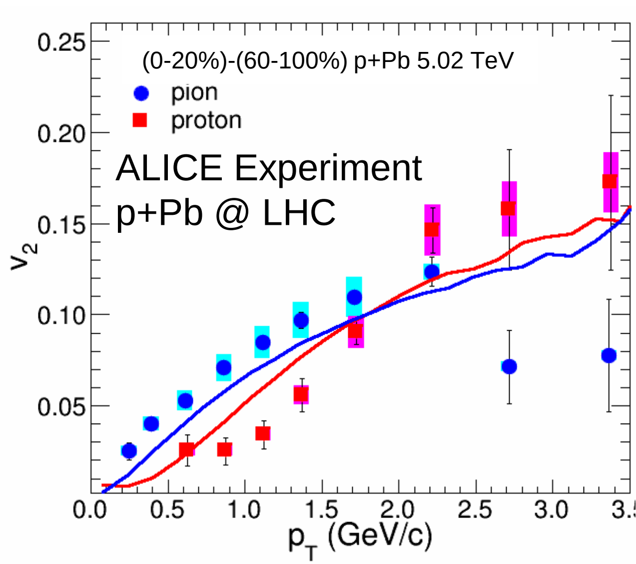
CMS: no subtraction of peripheral events!

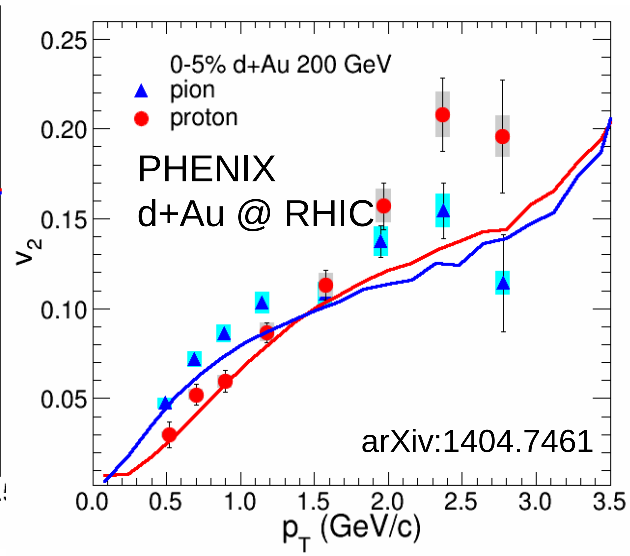
Flow from initial hotspots







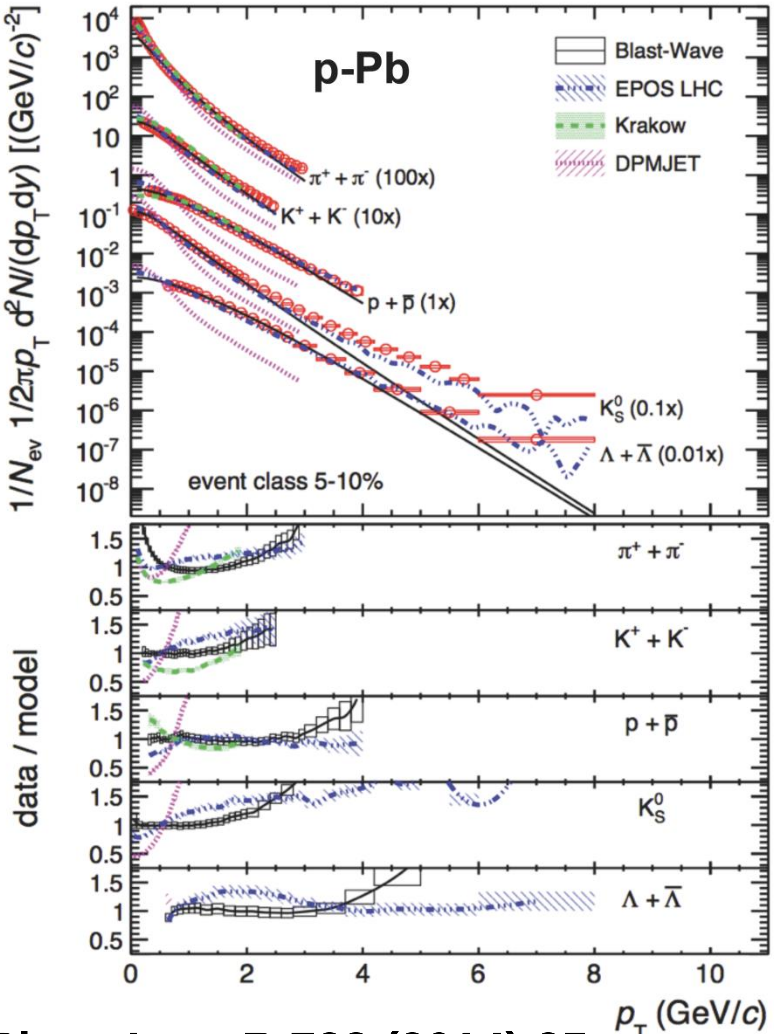




- Same behaviour observed at RHIC
- Geometrical engeneering
- Triangular flow patterns (?)

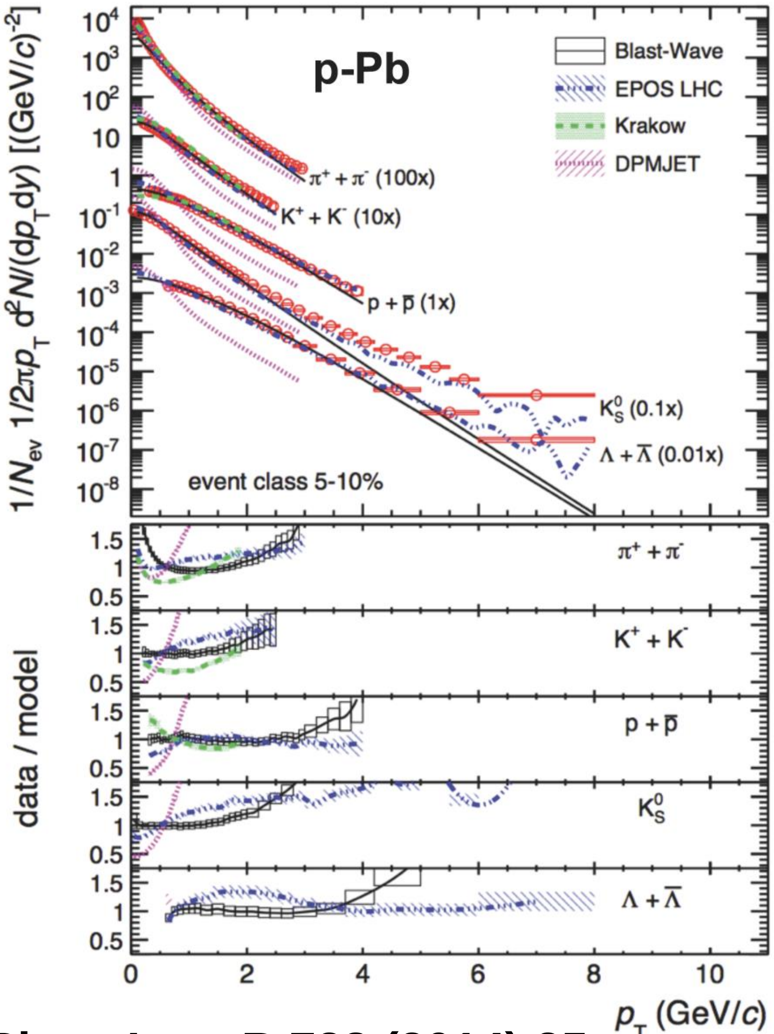
→ RHIC is running ^{3}He + Au right now!

pT-Spectra — radial flow?



Phys. Lett. B 728 (2014) 25

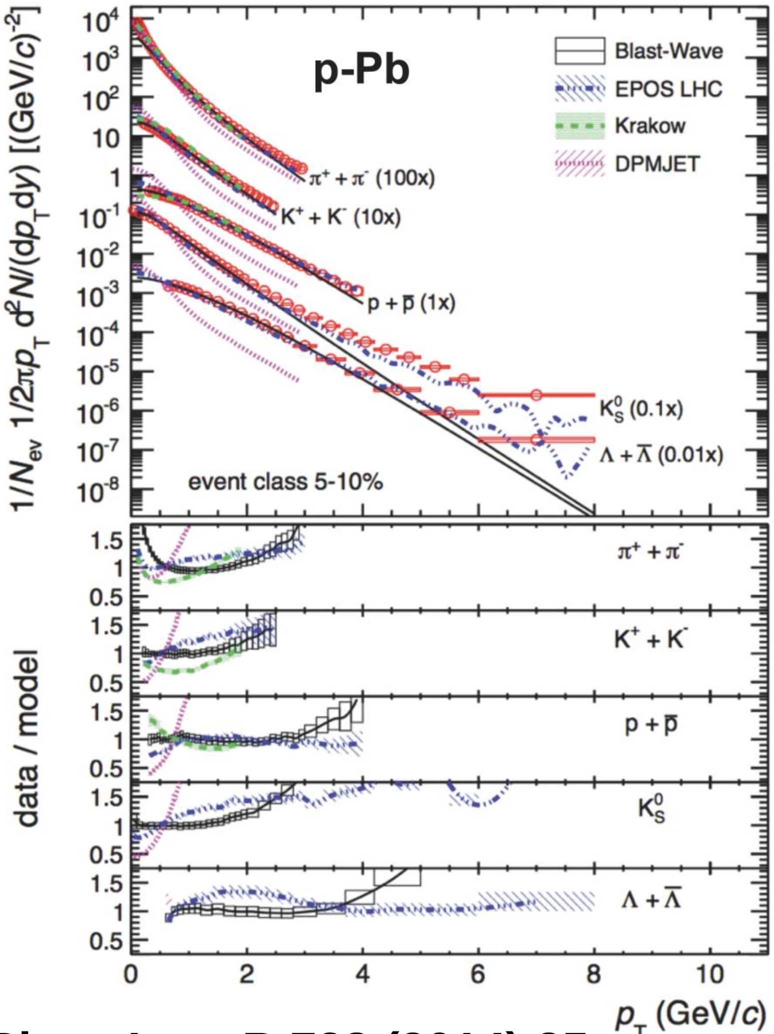
pT-Spectra — radial flow?



Phys. Lett. B 728 (2014) 25

Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

pT-Spectra — radial flow?

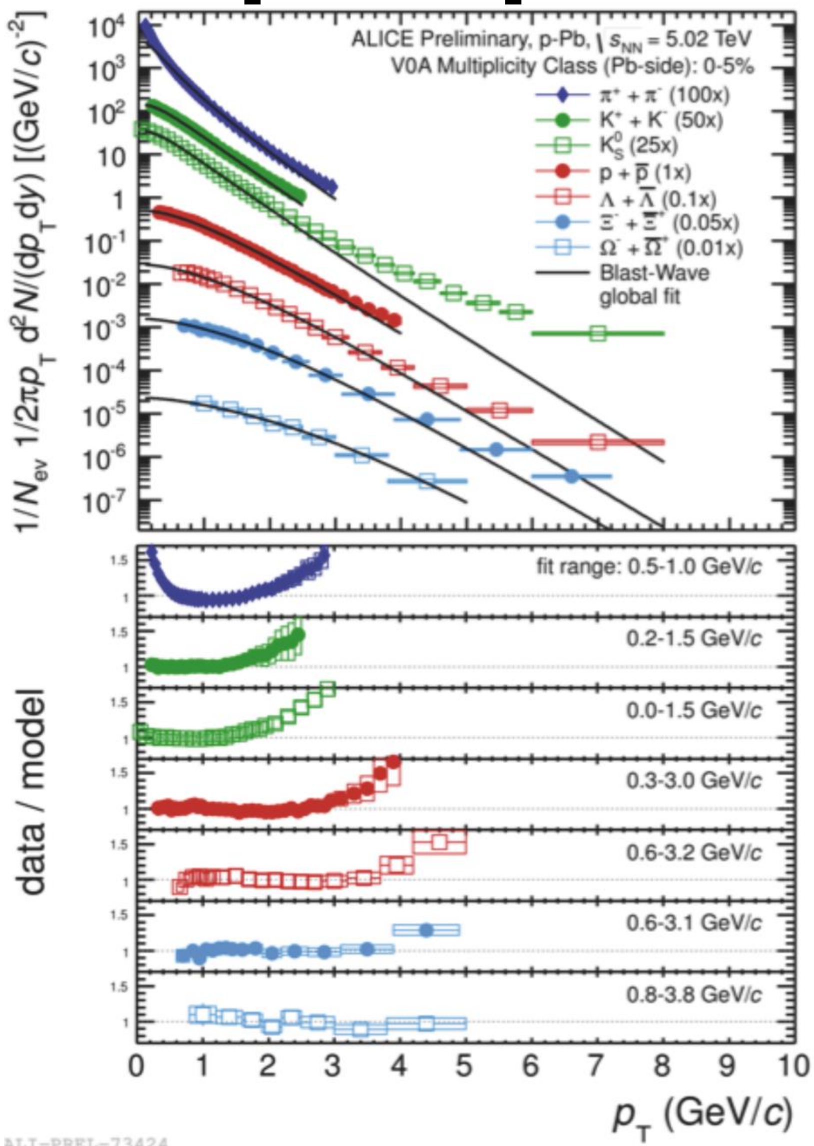


Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

A combined blast-wave fit to the data (**simplified hydro model** → T_{kin}, β) gives a reasonable description.

Phys. Lett. B 728 (2014) 25

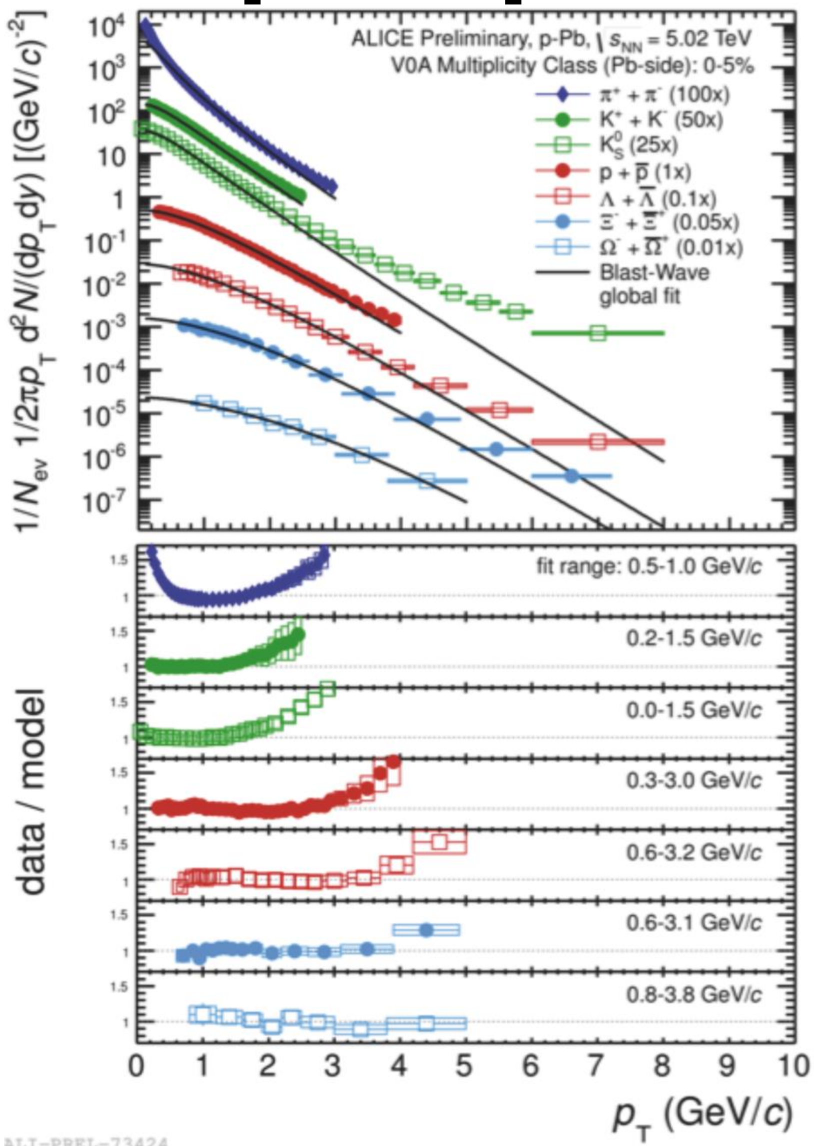
pT-Spectra — radial flow?

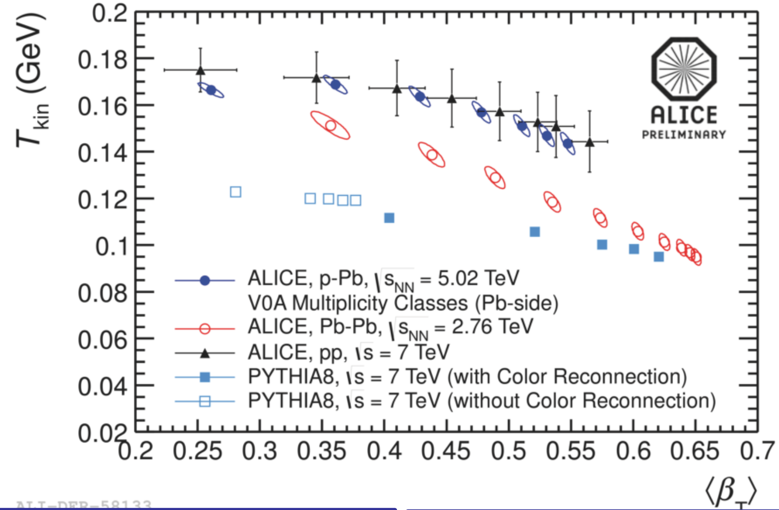


Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

A combined blast-wave fit to the data (**simplified hydro model** → T_{kin}, β) gives a reasonable description.

pT-Spectra — radial flow?

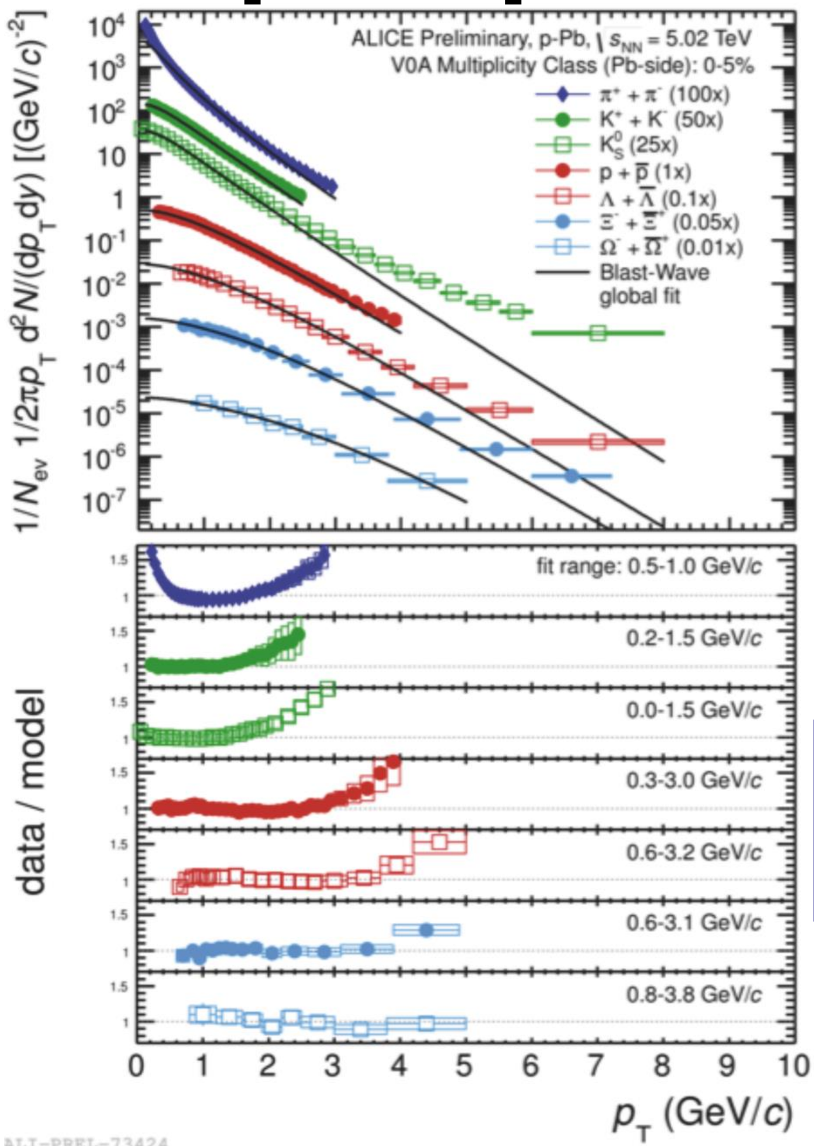


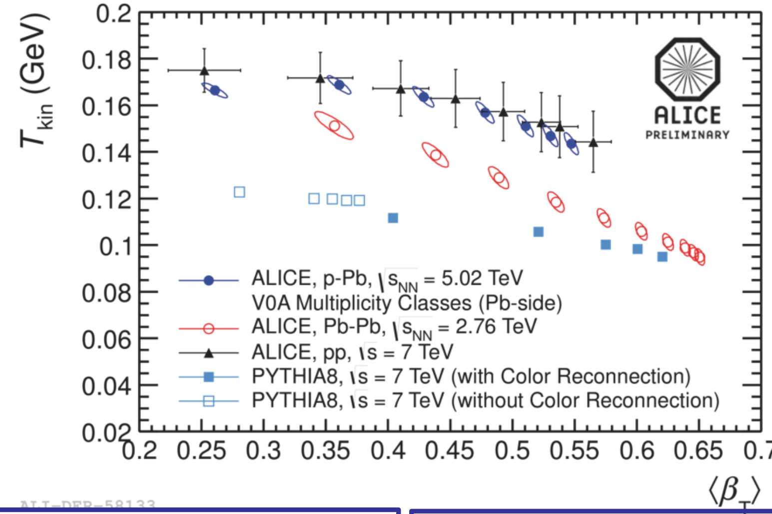


Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

A combined blast-wave fit to the data (**simplified hydro model** → T_{kin}, β) gives a reasonable description.

pT-Spectra — radial flow?



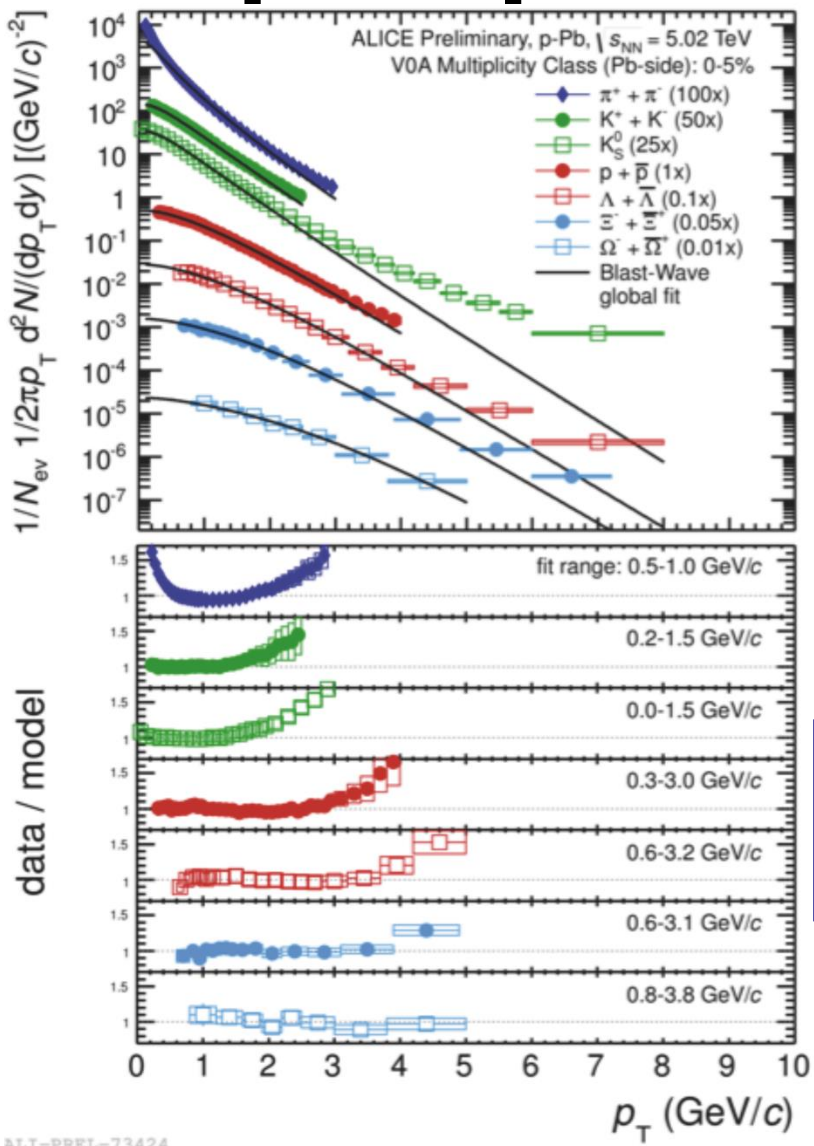


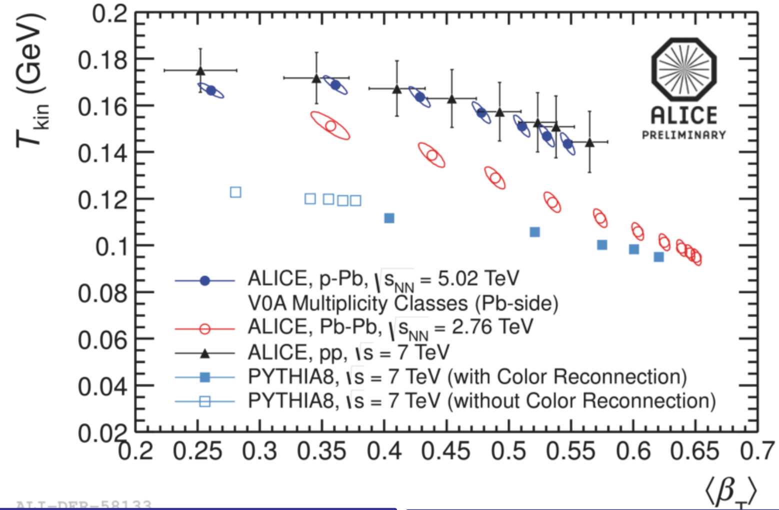
Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

A combined blast-wave fit to the data (**simplified hydro model** → T_{kin}, β) gives a reasonable description.

p-Pb and Pb-Pb data follow the same trend → consistent with a collective expansion.

pT-Spectra — radial flow?





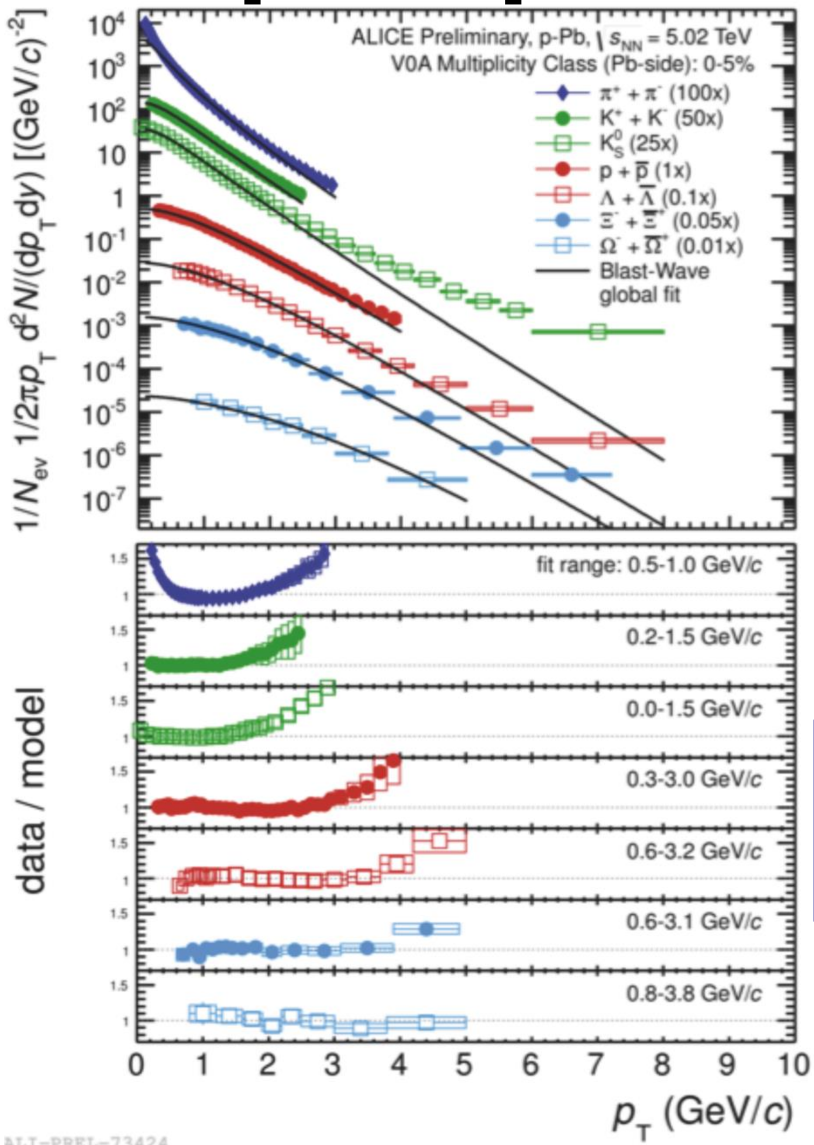
Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

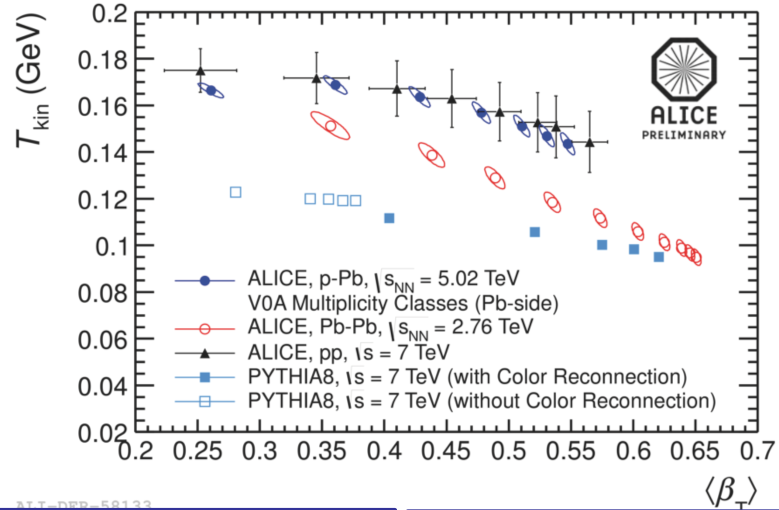
A combined blast-wave fit to the data (**simplified hydro model** → T_{kin}, β) gives a reasonable description.

p-Pb and Pb-Pb data follow the same trend → consistent with a collective expansion.

PYTHIA 8 with color reconnection shows a similar trend (without hydrodynamic flow).

pT-Spectra — radial flow?





Hydrodynamic models (EPOS, Krakow) show a better agreement than QCD inspired models (DPMJET).

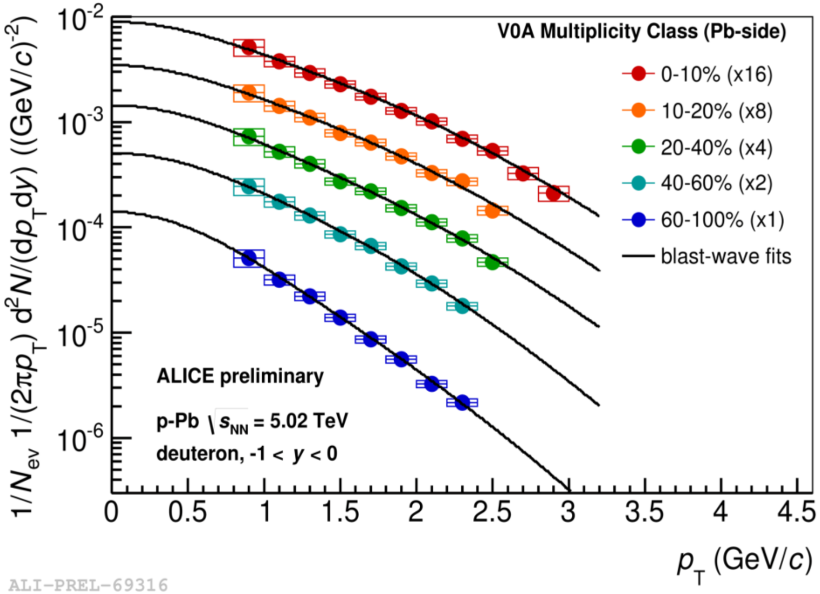
A combined blast-wave fit to the data (**simplified hydro model** → T_{kin}, β) gives a reasonable description.

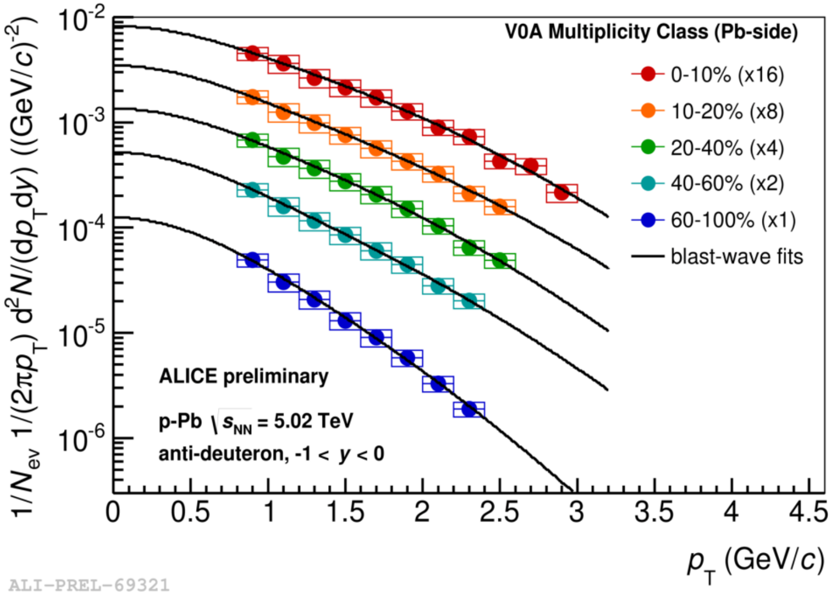
p-Pb and Pb-Pb data follow the same trend → consistent with a collective expansion.

PYTHIA 8 with color reconnection shows a similar trend (without hydrodynamic flow).

Other effects can mimic flow-like patterns!
And also pp data shows a similar trend

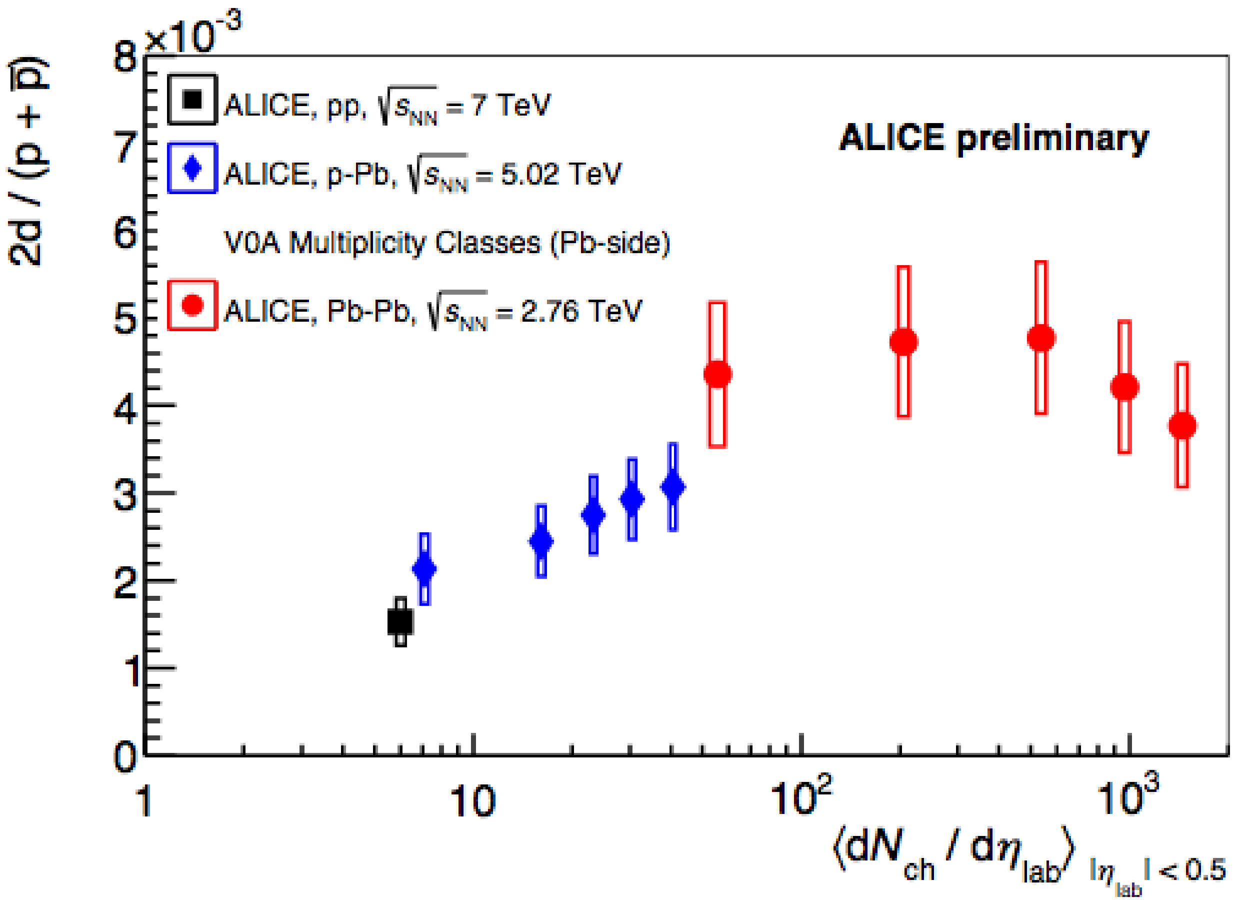
Even nuclei show this behaviour





- Deuterons and anti-deuterons are produced nearly equally in p-Pb collisions at the LHC
- Their p_T shape is well described with a simple hydro model

Deuteron-to-proton ratio



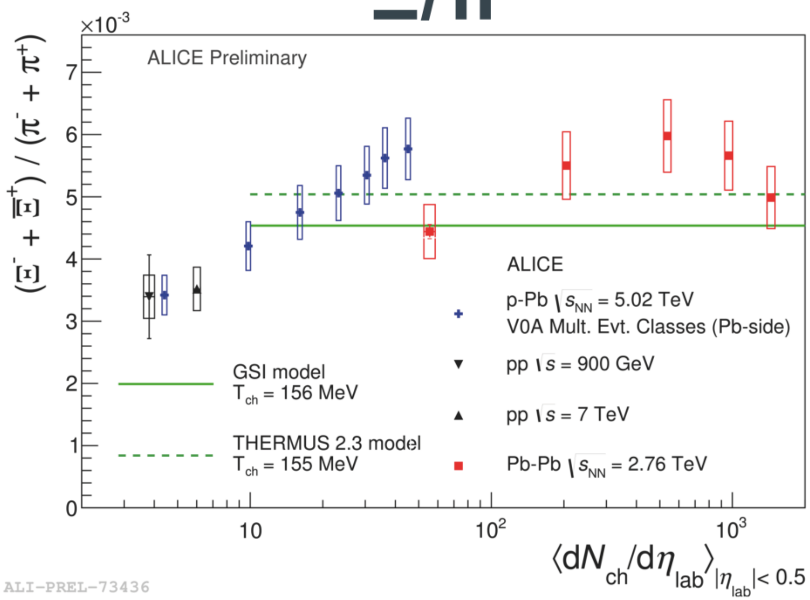
Rise with multiplicity

No further increase in Pb-Pb collisions within errors

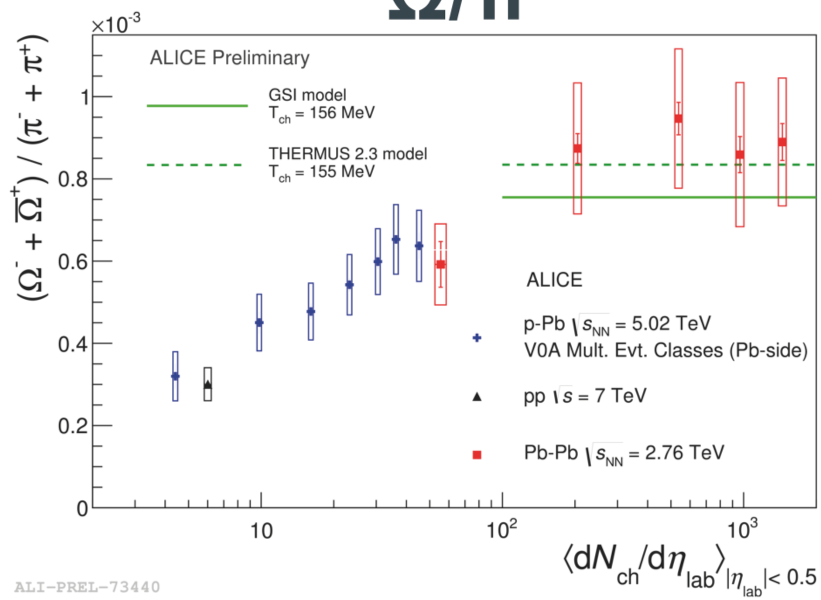
Particle yields and chemical equilibrium (1)

- Multi-strange particles are of particular interest as their production rate is sensitive to the system size.
- In high multiplicity p-Pb collisions similar values as in central Pb-Pb collisions are observed for Ξ (*dss*), not quite for Ω (*sss*).

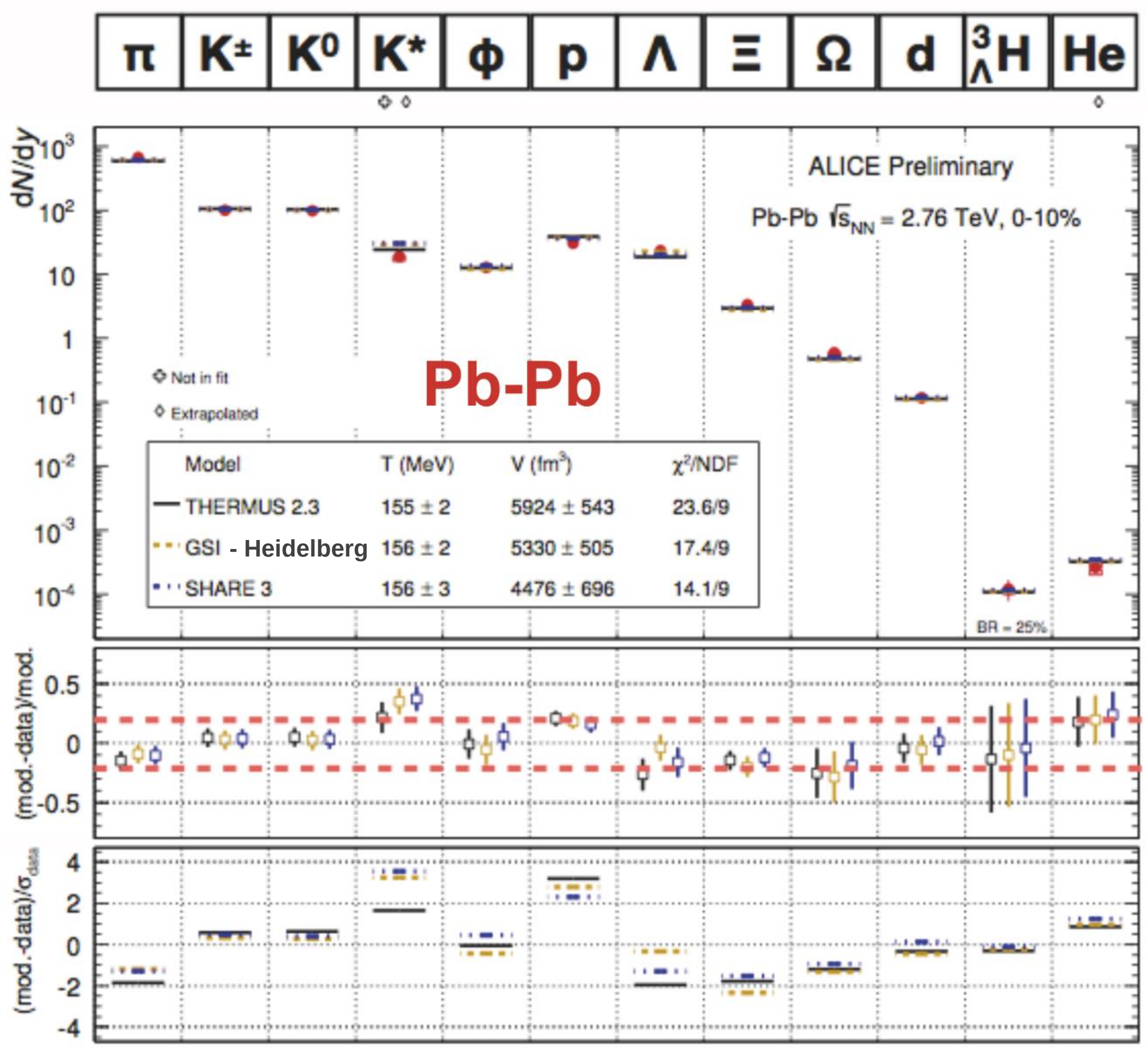
Ξ/π



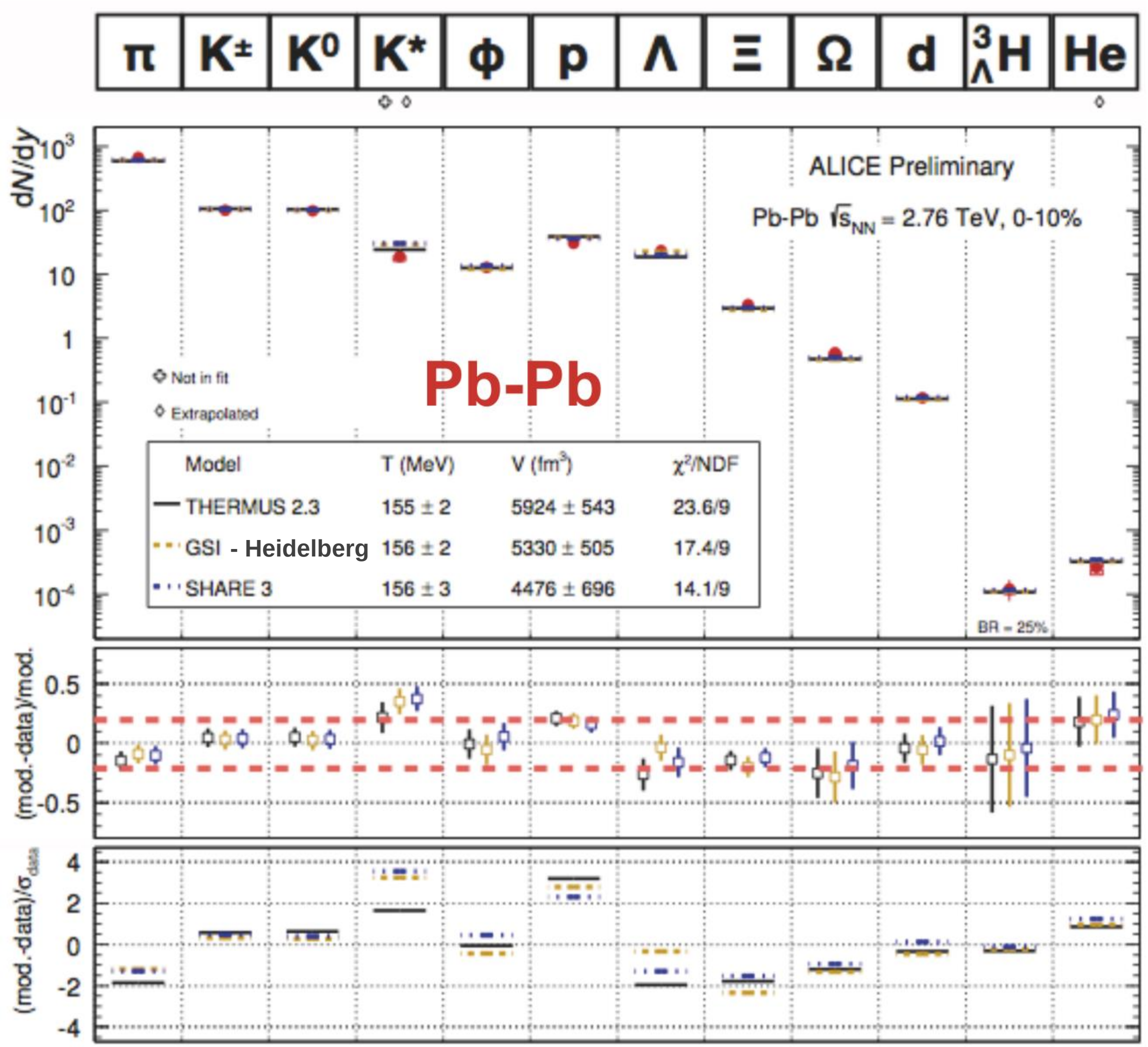
Ω/π



Particle yields and chemical equilibrium (2)

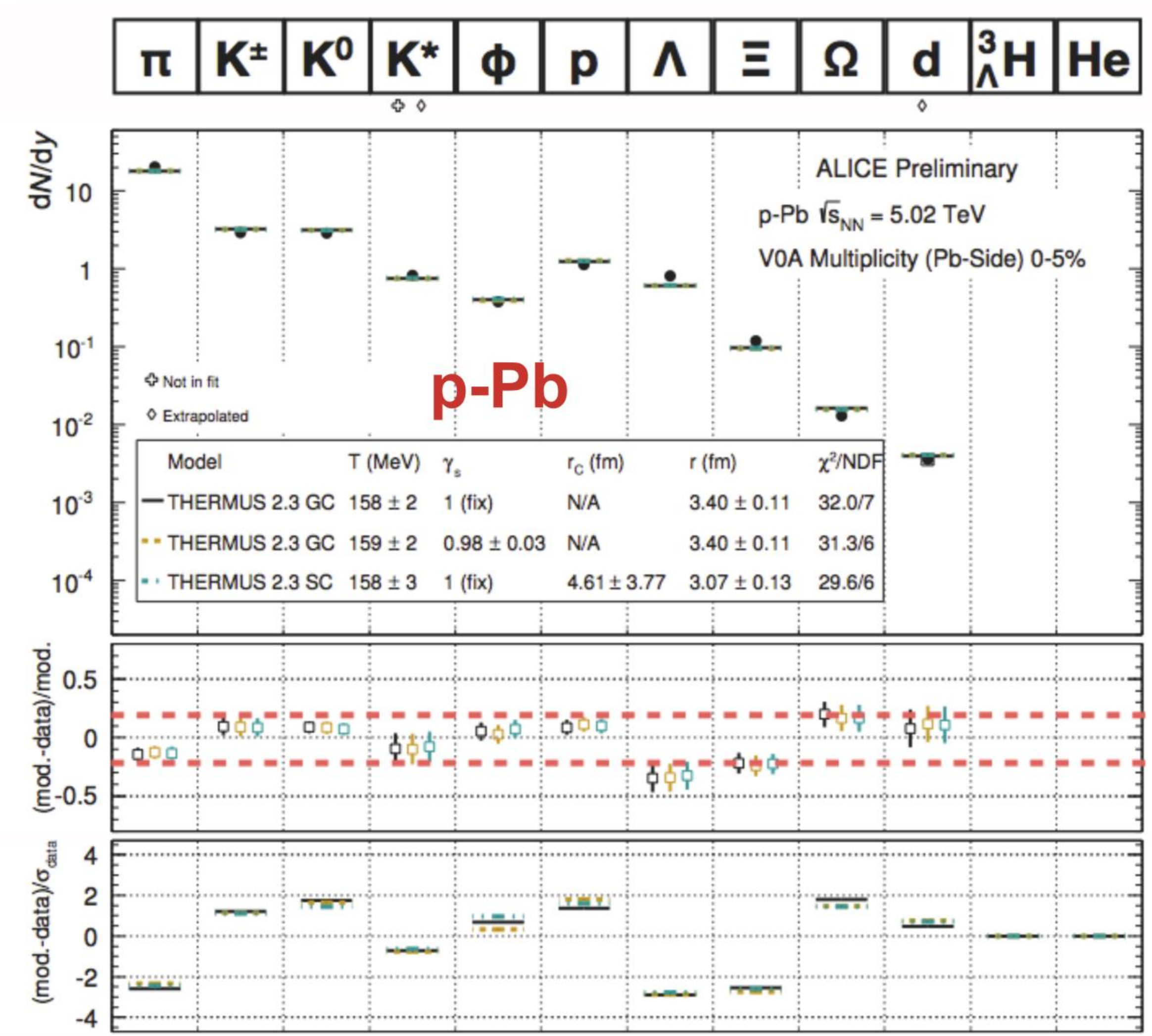


Particle yields and chemical equilibrium (2)



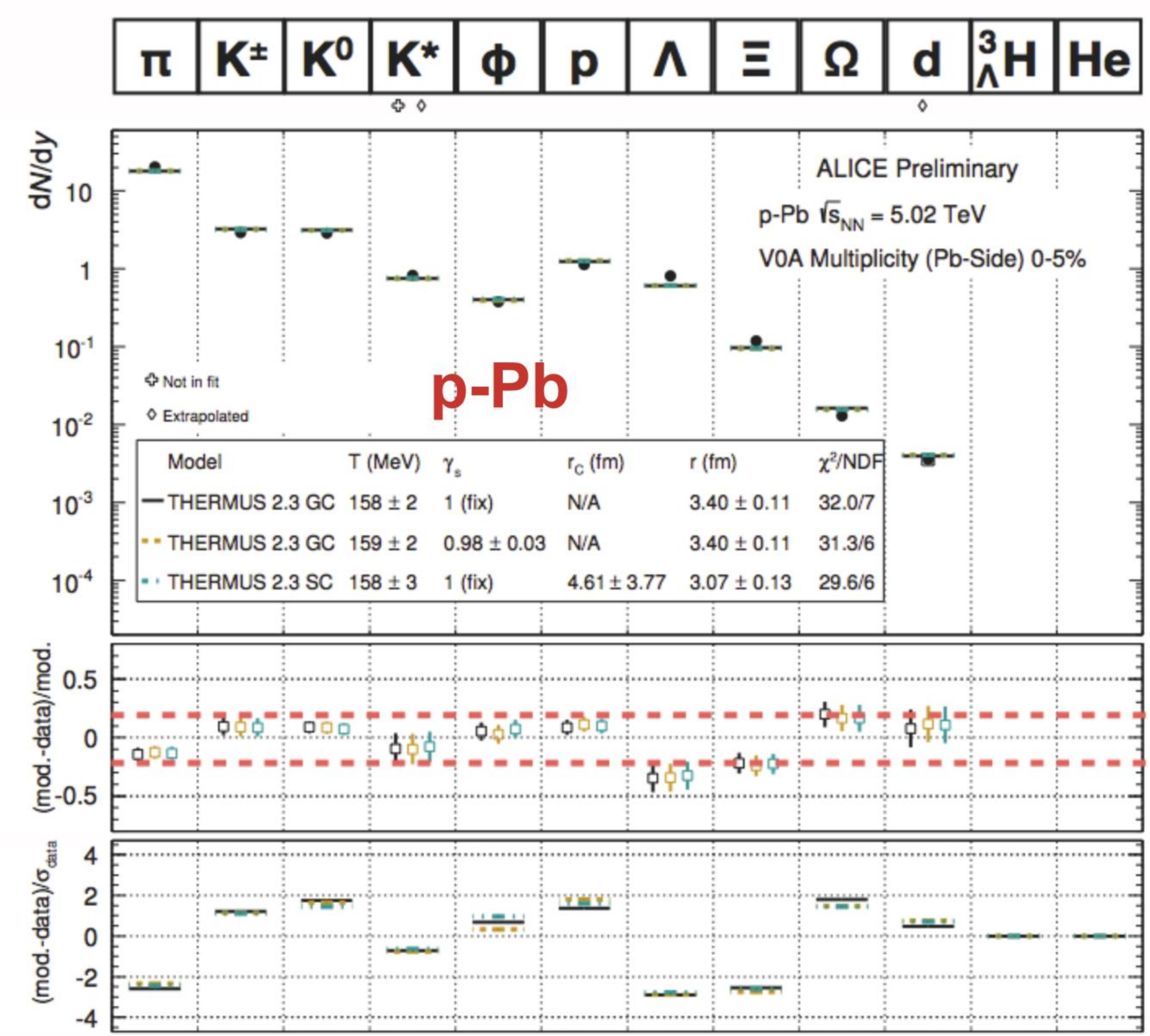
In heavy-ion collisions, chemical equilibrium is typically verified with a *thermal fit* in which all particle yields are described with the same chemical freeze-out temperature T_{ch}≈160 MeV.

Particle yields and chemical equilibrium (2)



In heavy-ion collisions, chemical equilibrium is typically verified with a *thermal fit* in which all particle yields are described with the same chemical freeze-out temperature T_{ch}≈160 MeV.

Particle yields and chemical equilibrium (2)

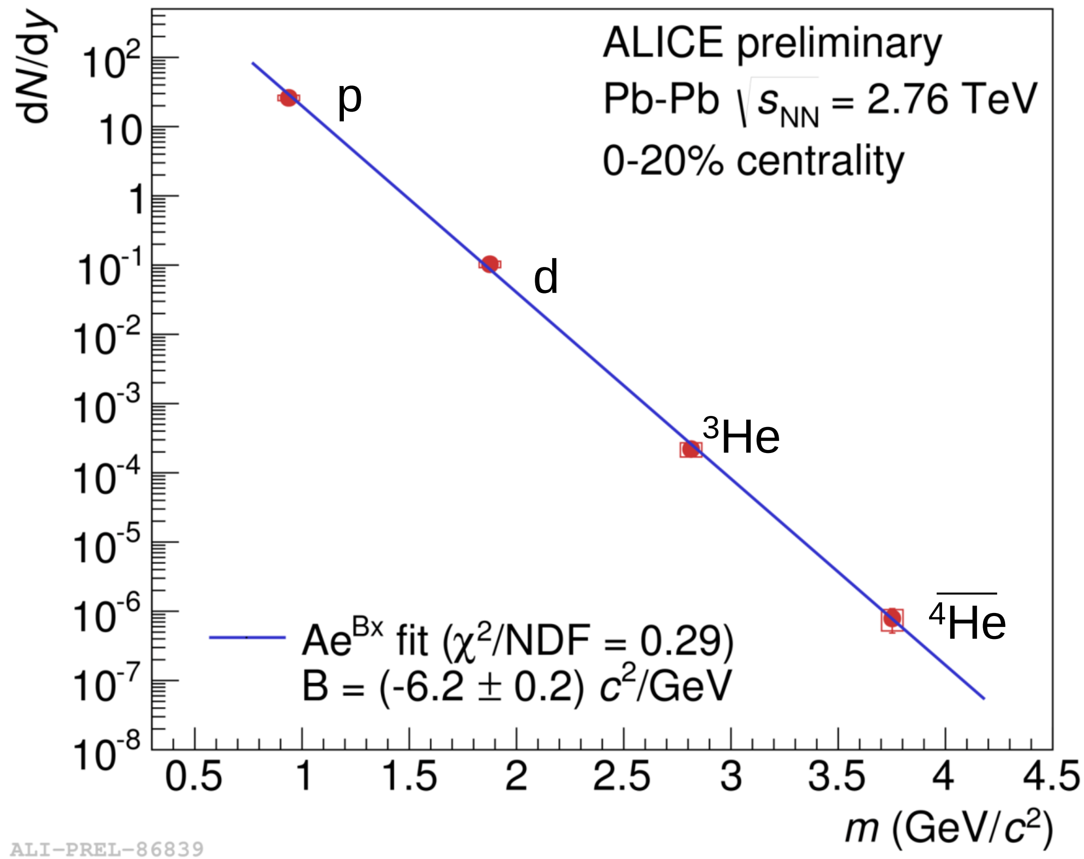


In heavy-ion collisions, chemical equilibrium is typically verified with a *thermal fit* in which all particle yields are described with the same chemical freeze-out temperature T_{ch}≈160 MeV.

Works in 1st order also in p-Pb collisions, however, the χ^2/ndof is slightly worse: ≈5 instead of ≈2, mainly due to multi-strange particles.

Nuclei in Pb-Pb

- Thermal model: production yield dN/dy ~ exp(-m/T)
- Nuclei follow the exponential fall predicted by the model nicely
- Each added baryon gives a factor of ~300 less production yield

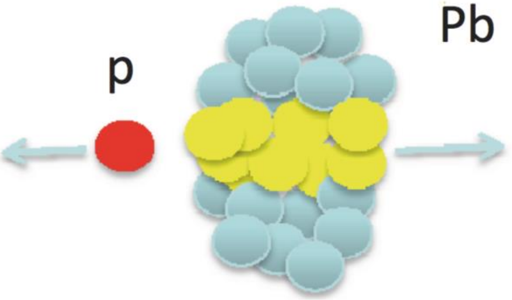


High p_T and jets

What is the R_{pA}?

- Modification of the spectral shape due to nuclear effects is quantified based on the nuclear modification factor:

$$R_{pA} = \frac{dN_{pA} / dp_T}{\langle N_{coll} \rangle dN_{pp} / dp_T}$$

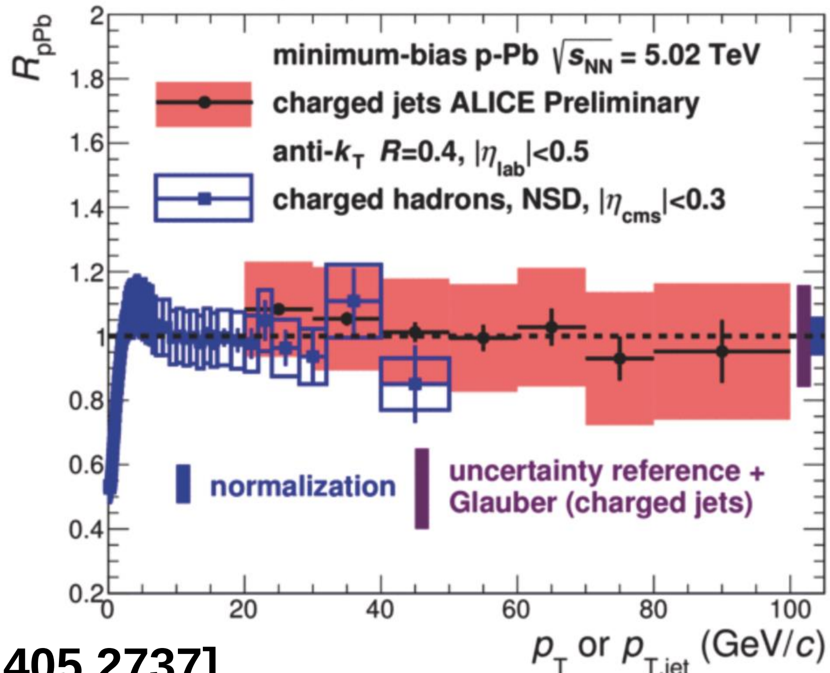


- Number of binary collisions is calculated in a Glauber model: $\langle N_{coll} \rangle = 6.9 \pm 0.6$
- For pQCD processes: if $R_{pA} \approx 1 \rightarrow$ p-Pb collision is approximately a superposition of independent proton-nucleon collisions and no nuclear effects are present.

R_{pA} — examples

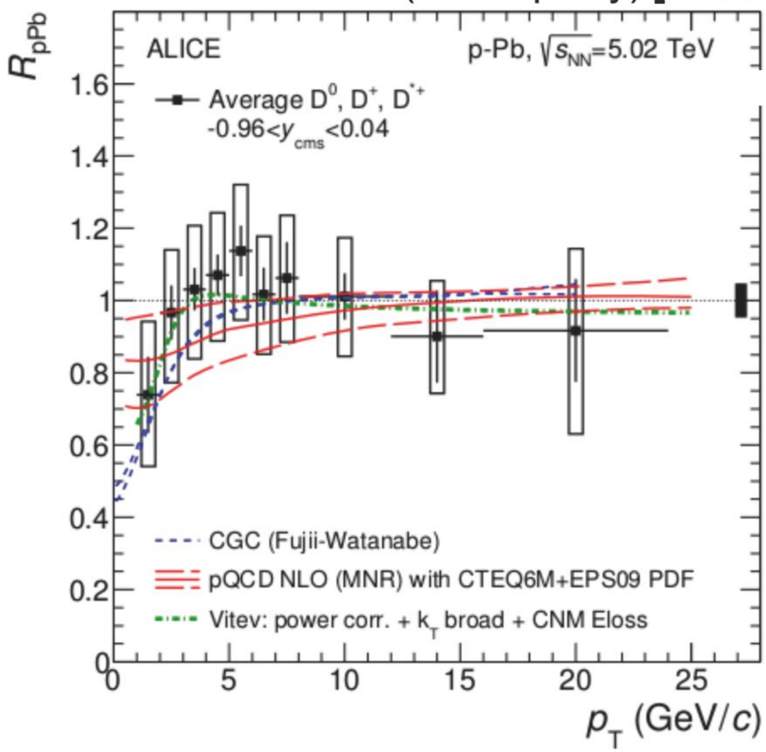
[1405.3452]

charged particles and jets



[1405.2737]

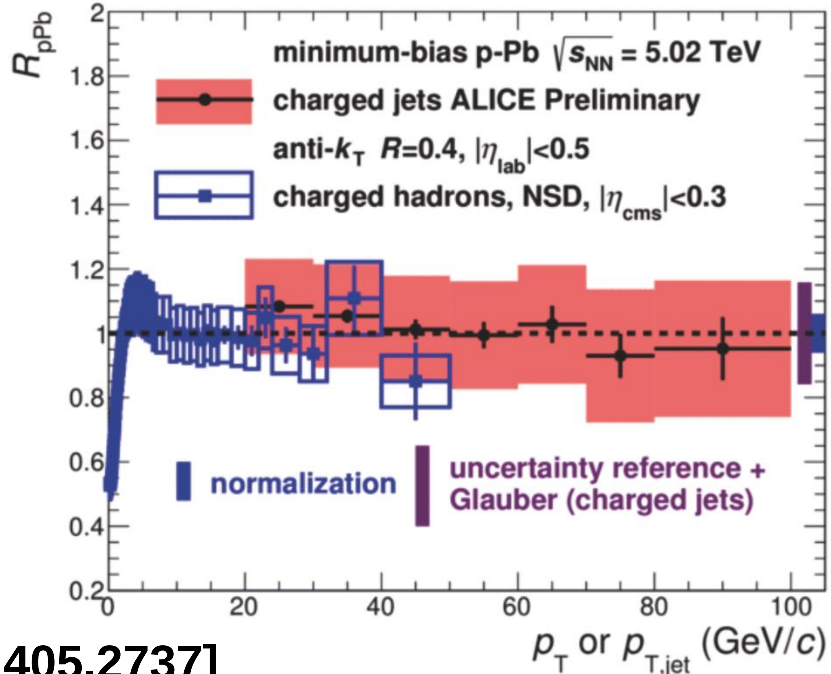
D mesons (mid-rapidity)



R_{pA} — examples

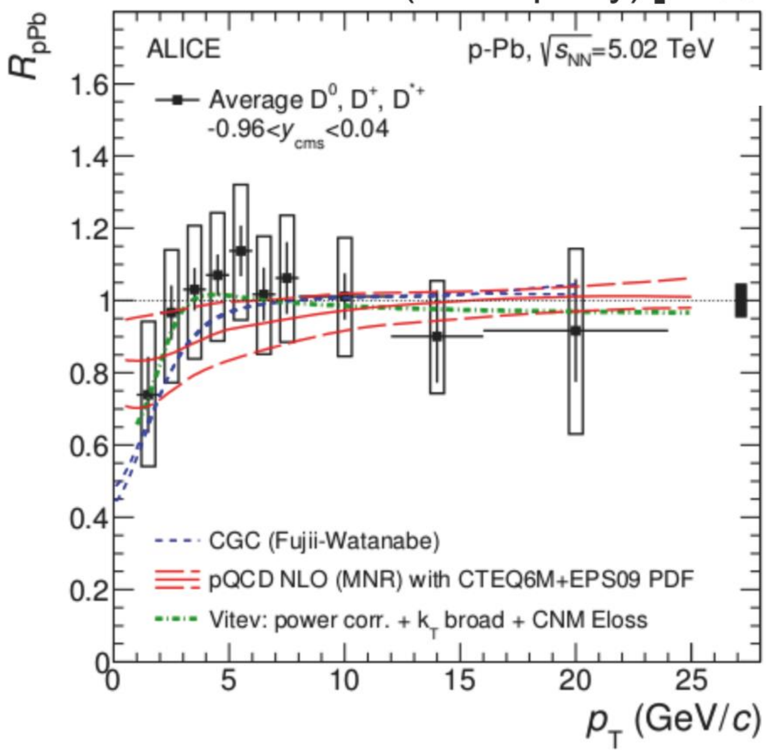
[1405.3452]

charged particles and jets



[1405.2737]

D mesons (mid-rapidity)

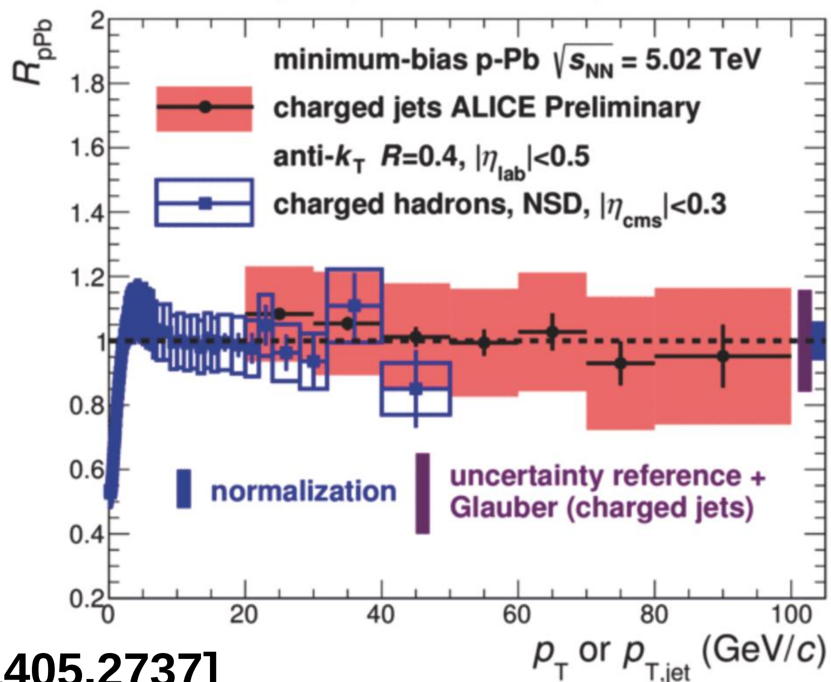


In general, no significant modification observed in the 10-30 GeV/c region.

R_{pA} — examples

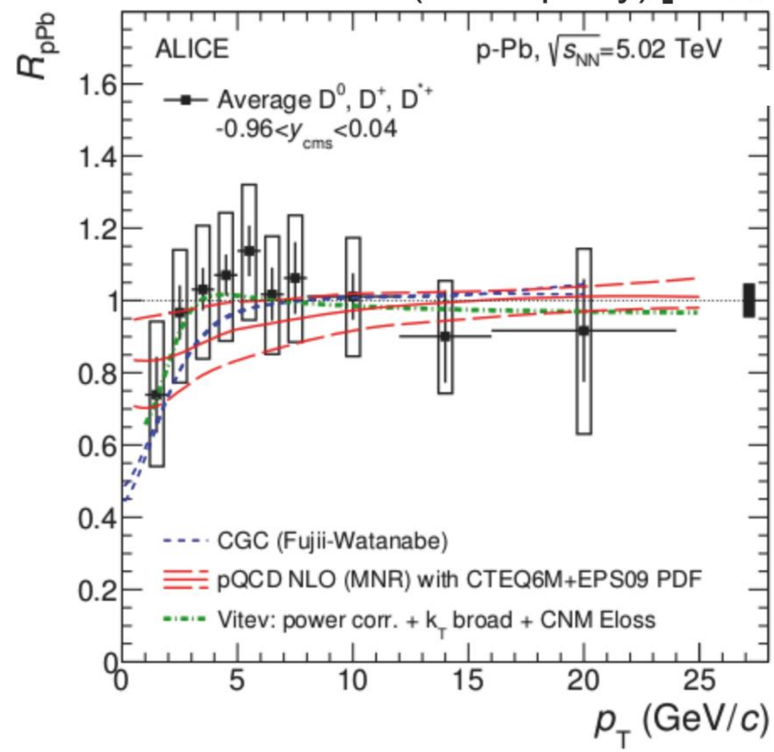
[1405.3452]

charged particles and jets



[1405.2737]

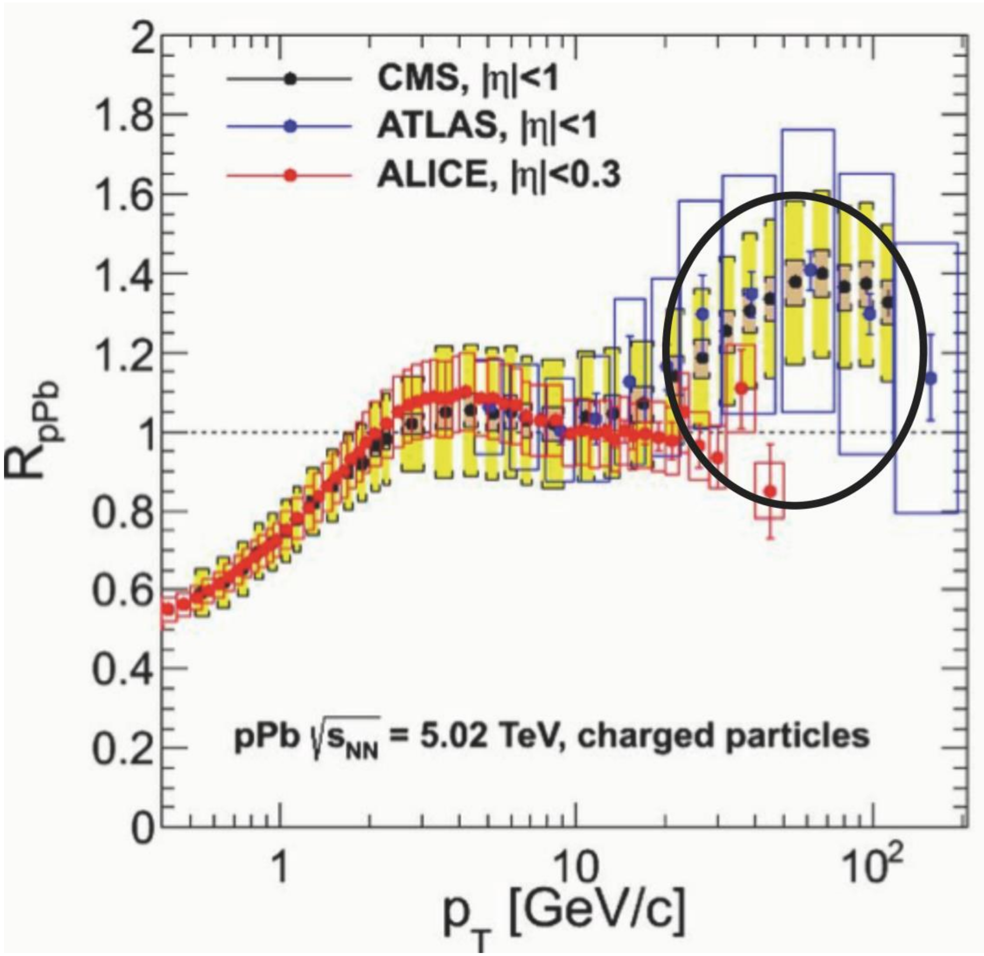
D mesons (mid-rapidity)



In general, no significant modification observed in the 10-30 GeV/c region.

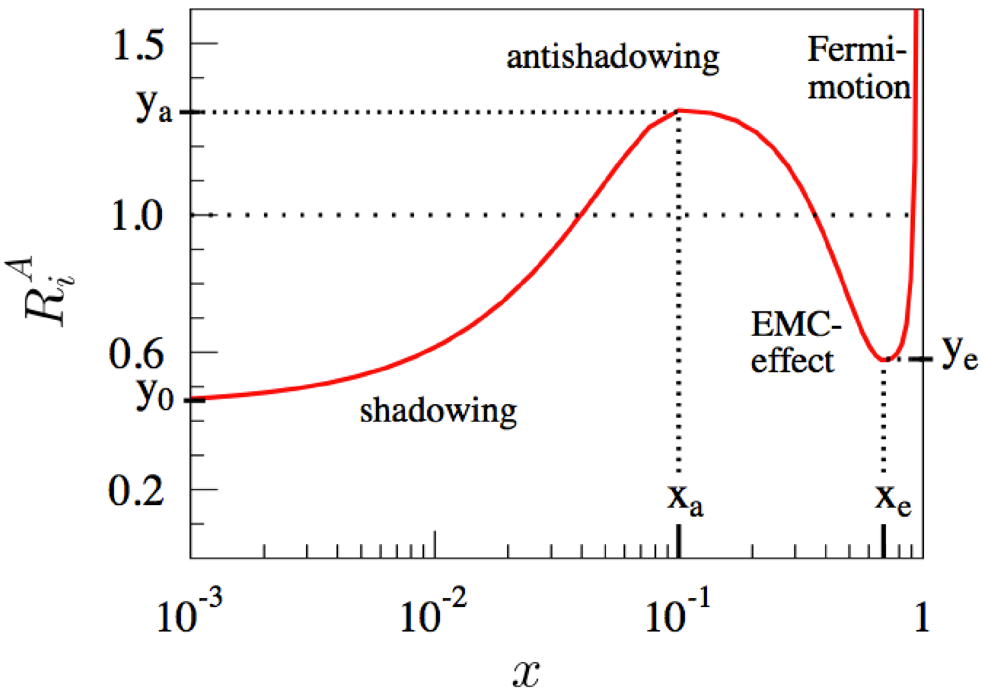
The suppression effects seen in AA collisions are not due to cold nuclear matter effects. They are final state effects in AA (energy lost in the medium).

Charged particle R_{pA}



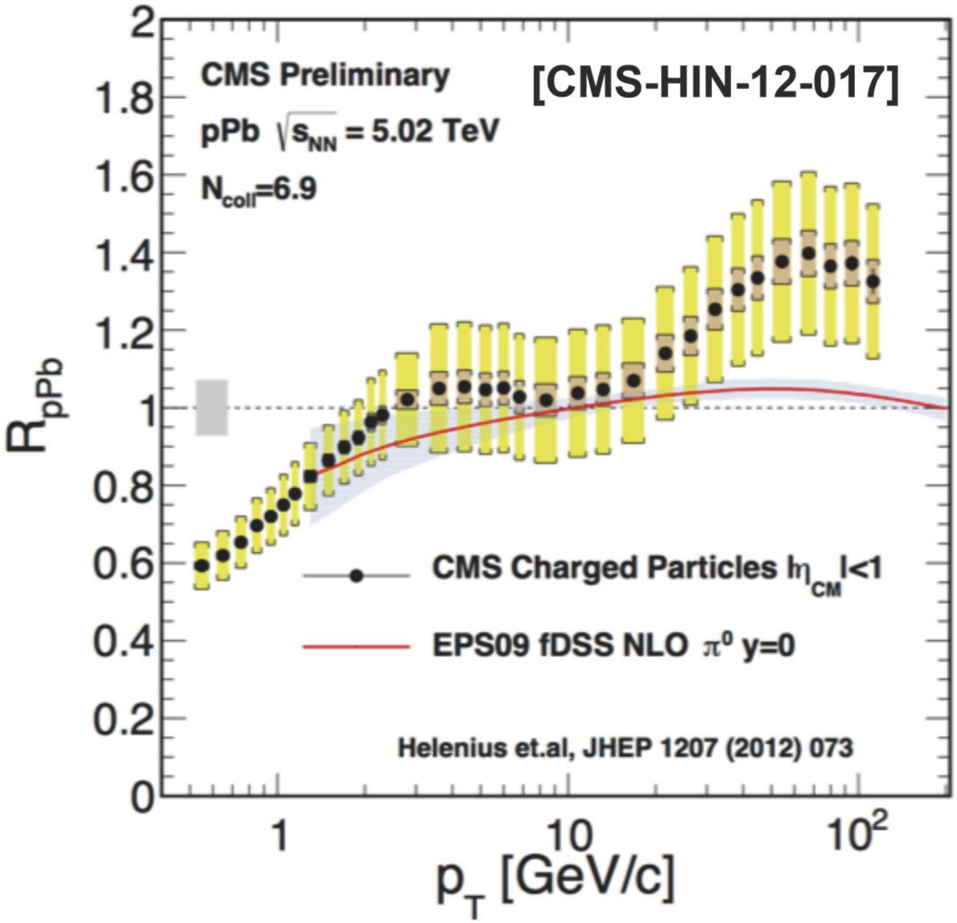
- Going to even higher p_T, CMS observed an enhancement in the charged particle R_{pA}. ATLAS now confirms this observation.
- No explanation yet for this phenomenon!
- PDFs are expected to be modified in the nucleus. However, antishadowing seems to be insufficient.
- Jet fragmentation needs to be checked, because the R_{pA} of jets is approximately equal to one in all three experiments.
- Different impression of CMS/ATLAS vs. ALICE data.

Charged particle R_{pA}



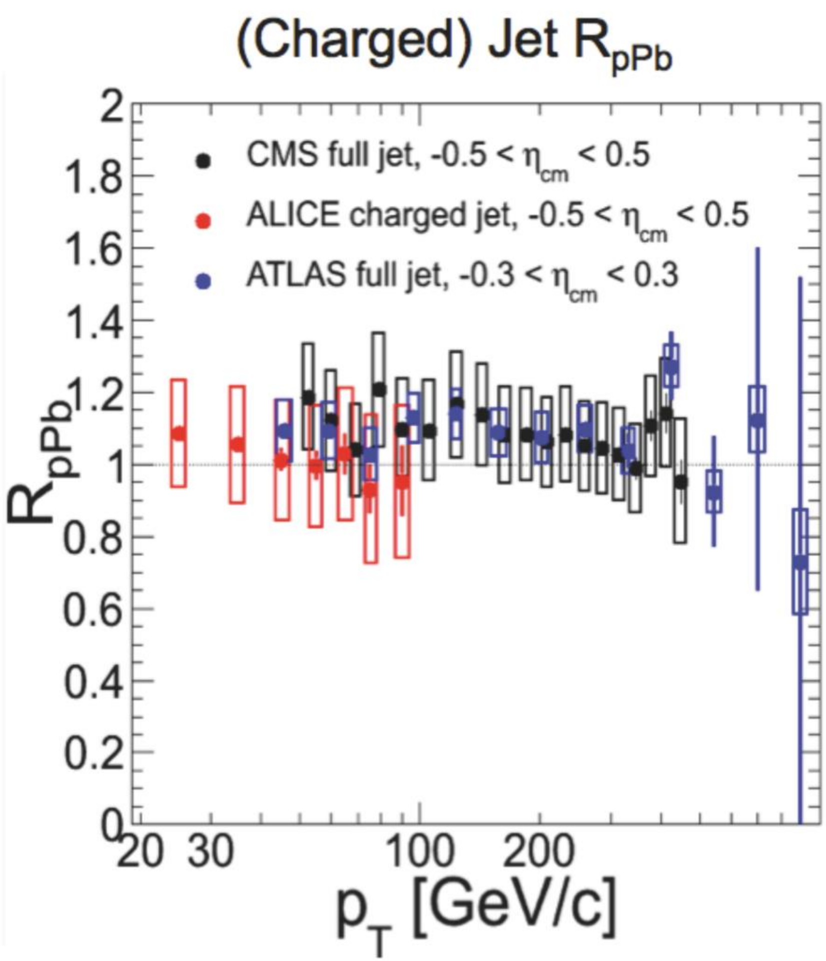
- Going to even higher p_T, CMS observed an enhancement in the charged particle R_{pA}. ATLAS now confirms this observation.
- No explanation yet for this phenomenon!
- PDFs are expected to be modified in the nucleus. However, antishadowing seems to be insufficient.
- Jet fragmentation needs to be checked, because the R_{pA} of jets is approximately equal to one in all three experiments.
- Different impression of CMS/ATLAS vs. ALICE data.

Charged particle R_{pA}



- Going to even higher p_T, CMS observed an enhancement in the charged particle R_{pA}. ATLAS now confirms this observation.
- No explanation yet for this phenomenon!
- PDFs are expected to be modified in the nucleus. However, antishadowing seems to be insufficient.
- Jet fragmentation needs to be checked, because the R_{pA} of jets is approximately equal to one in all three experiments.
- Different impression of CMS/ATLAS vs. ALICE data.

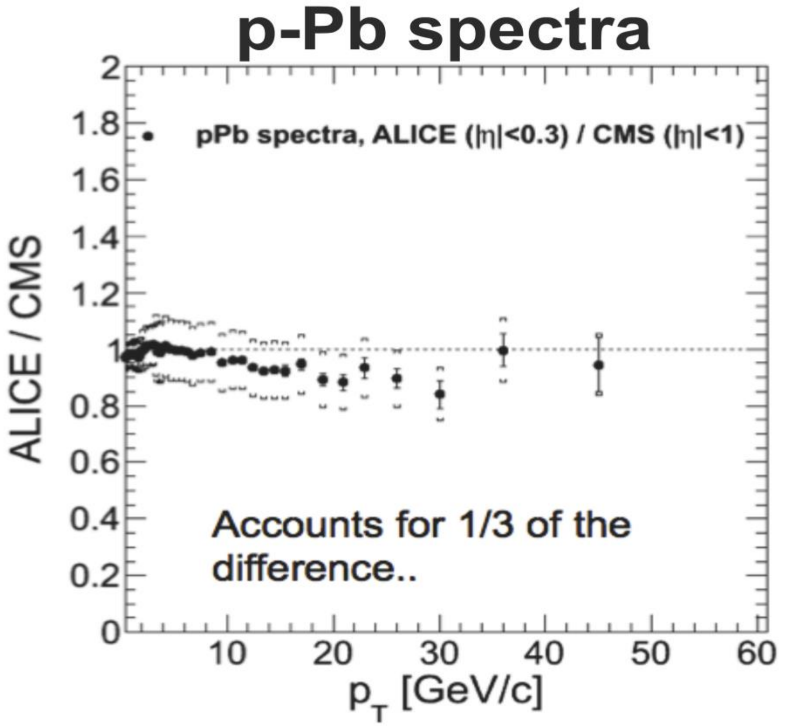
Charged particle R_{pA}

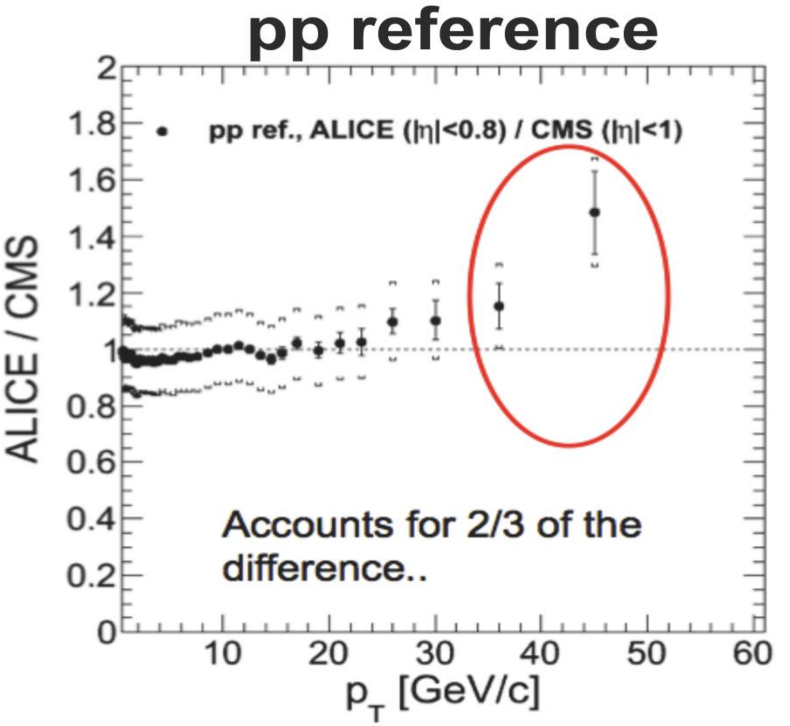


- Going to even higher p_T, CMS observed an enhancement in the charged particle R_{pA}. ATLAS now confirms this observation.
- No explanation yet for this phenomenon!
- PDFs are expected to be modified in the nucleus. However, antishadowing seems to be insufficient.
- Jet fragmentation needs to be checked, because the R_{pA} of jets is approximately equal to one in all three experiments.
- Different impression of CMS/ATLAS vs. ALICE data.

The need for 5 TeV pp reference data

• N.B.: There is no data at the reference energy! The proton spectrum is interpolated/extrapolated from 2.76 TeV and 7 TeV data…

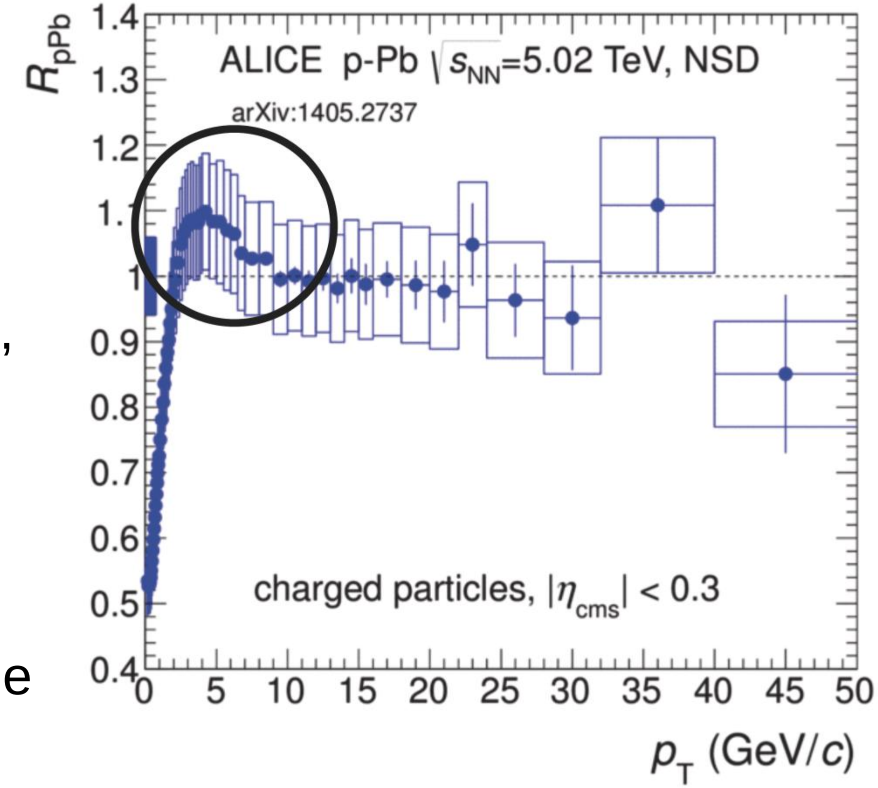




• Also needed for: 13 TeV * 82 / 208 = 5.125 TeV !

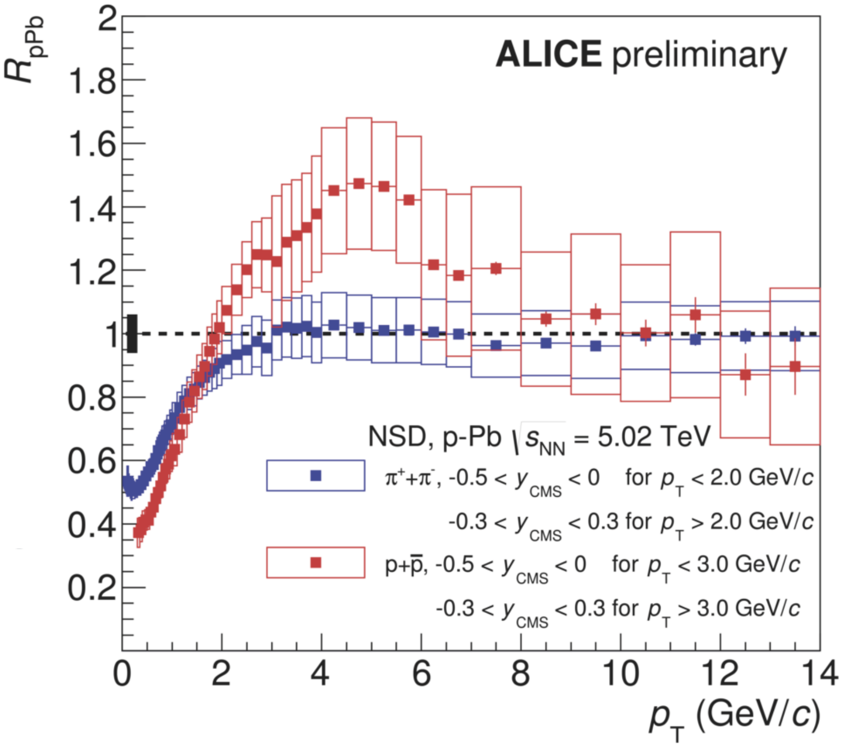
R_{pA} at intermediate p_T

- The second interesting region is around 3-6 GeV/c → Cronin peak
- Shows a strong dependence on particle type:
    - no peak for pions and kaons,
    - rather pronounced for protons..
- This could indicate that it is caused by the mass dependent hardening of the p_T-spectra as predicted by the radial flow picture.

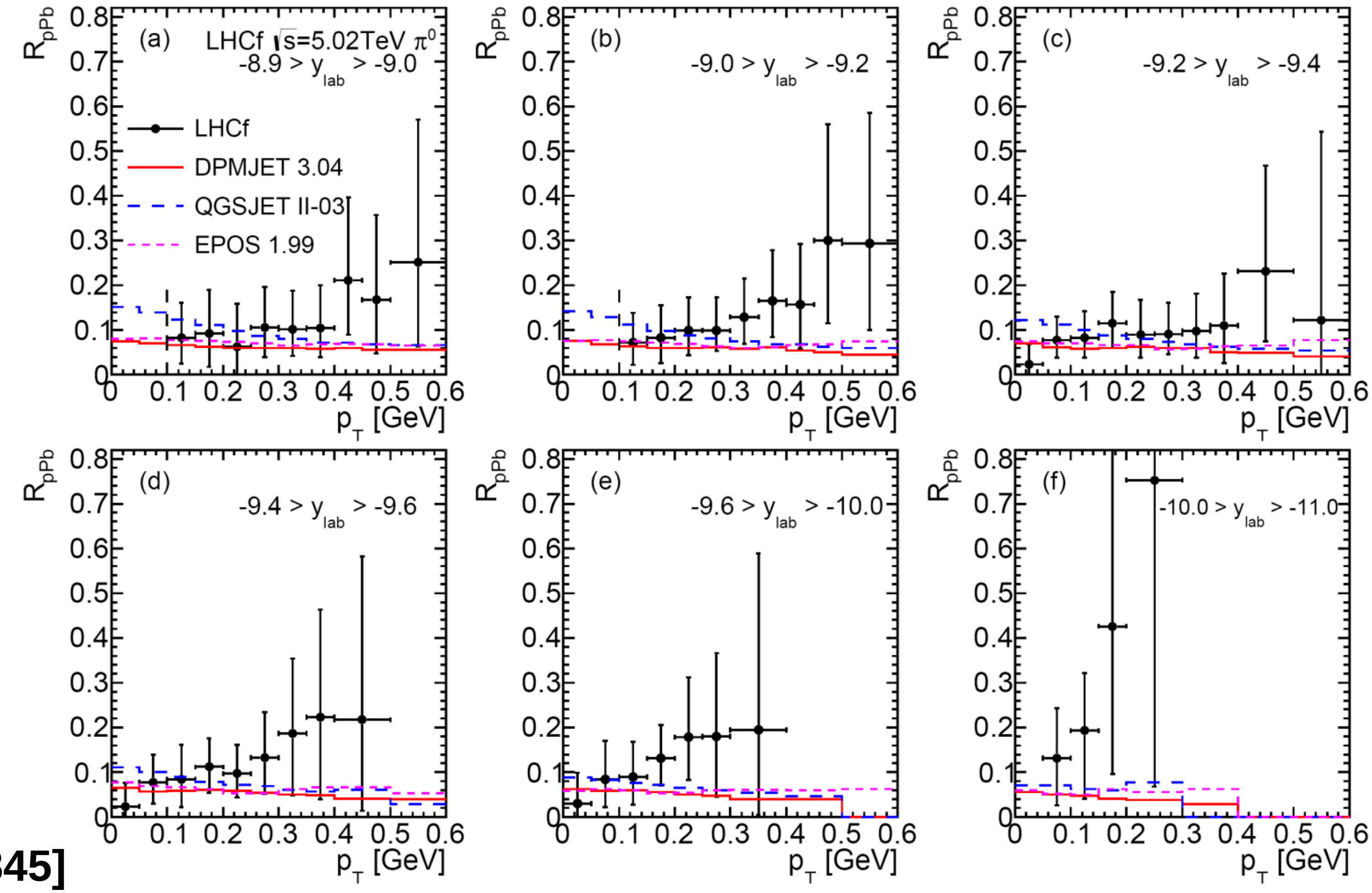


R_{pA} at intermediate p_T

- The second interesting region is around 3-6 GeV/c → Cronin peak
- Shows a strong dependence on particle type:
  - no peak for pions and kaons,
  - rather pronounced for protons..
- This could indicate that it is caused by the mass dependent hardening of the p_T-spectra as predicted by the radial flow picture.



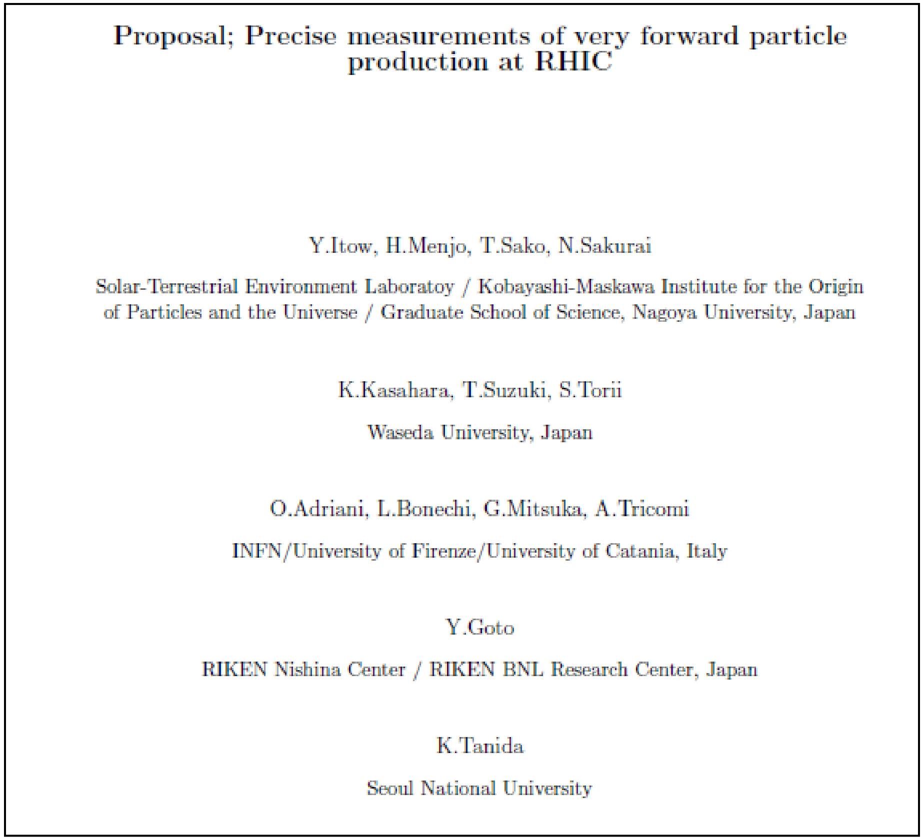
LHCf R_{pA} measurement



[1403.7845]

- R_{pA} measured at low p_T (< 0.6 GeV/c) and very forward (y < -8.9).
- Reproduced by models, helps to model nuclear effects in cosmic ray air showers.

RHICf and PHENIX



Proposal; Precise measurements of very forward particle production at RHIC

Y.Itow, H.Menjo, T.Sako, N.Sakurai

Solar-Terrestrial Environment Laboratoy / Kobayashi-Maskawa Institute for the Origin of Particles and the Universe / Graduate School of Science, Nagoya University, Japan

K.Kasahara, T.Suzuki, S.Torii

Waseda University, Japan

O.Adriani, L.Bonechi, G.Mitsuka, A.Tricomi

INFN/University of Firenze/University of Catania, Italy

Y.Goto

RIKEN Nishina Center / RIKEN BNL Research Center, Japan

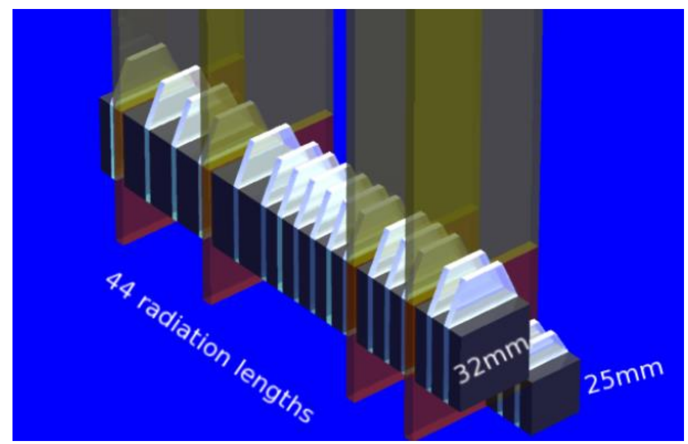
K.Tanida

Seoul National University

https://indico.bnl.gov/getFile.py/access?resId=0&materialId=6&confId=764

LHCf experiment measures very forward particle production at the LHC for constraining cosmic shower models

Proposal for **RHICf** experiment to make comparable measurements in p+p and p+A collisions at RHIC

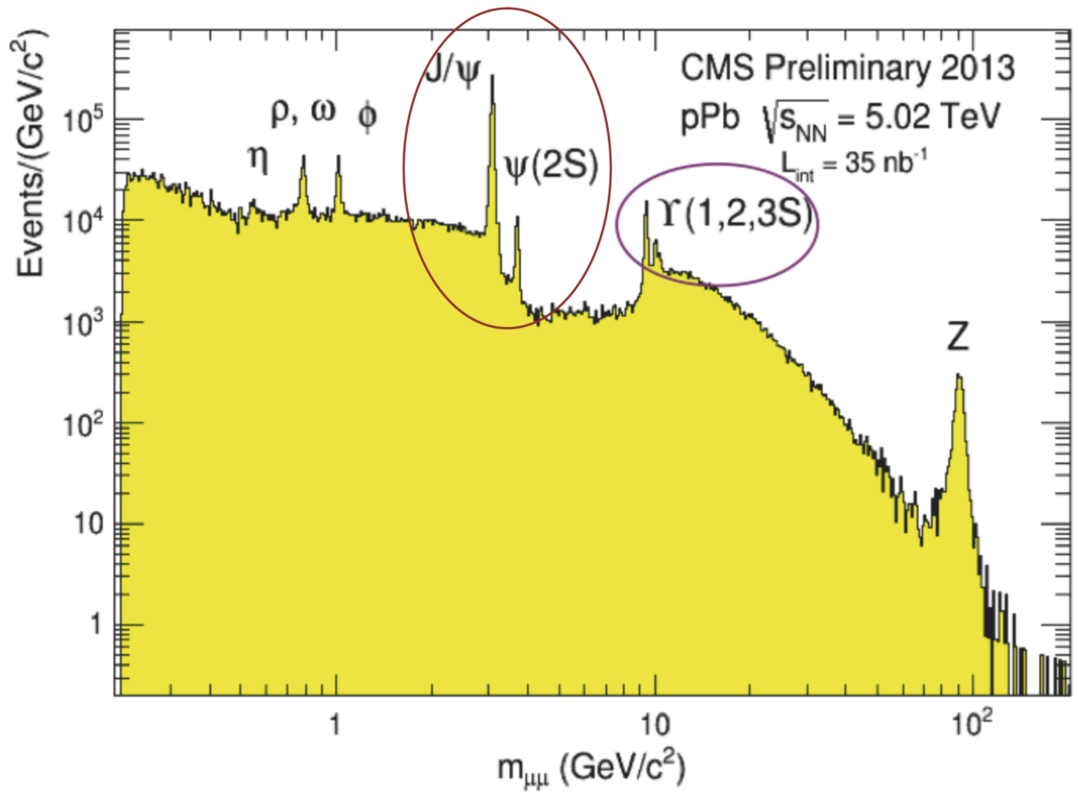


If approved, RHICf detector would be integrated with the PHENIX experiment providing key additional constraints

Heavy flavour and electroweak bosons

Quarkonia — Introduction

- A precise measurement of quarkonia is crucial for the understanding of *regeneration* effects in Pb-Pb collisions which probe de-confinement in Pb-Pb.
- In addition, these measurements can help to constrain nuclear PDFs.



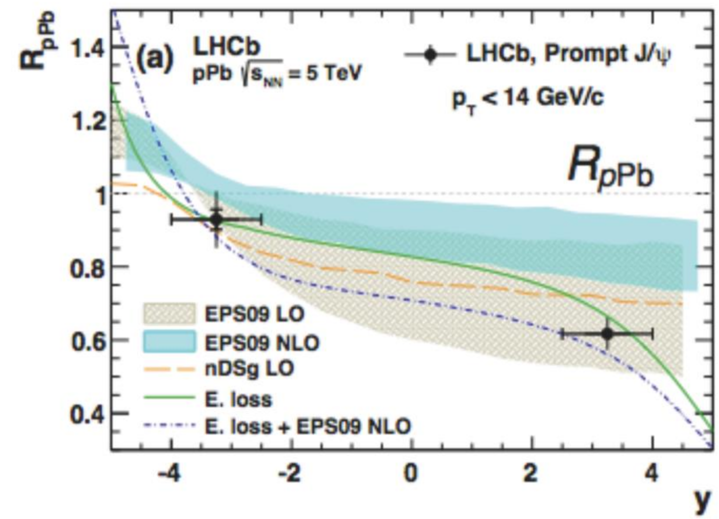
Quarkonia (1)

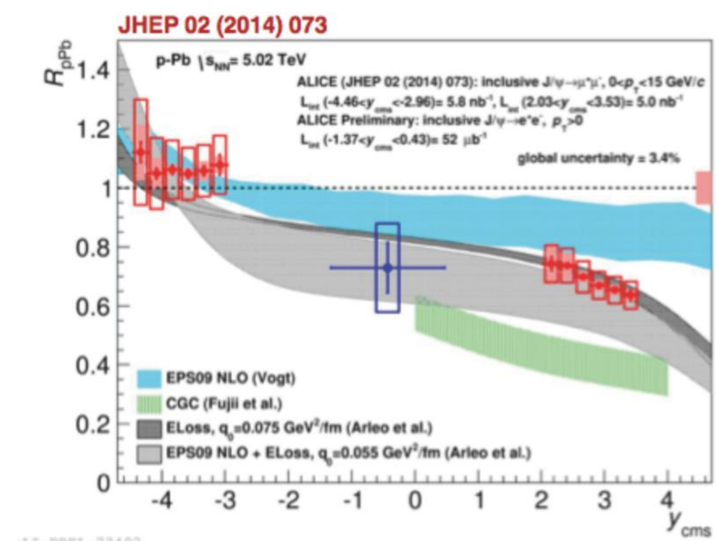
- In general, nuclear absorption effects are small at the LHC. Precision of the data allows for quantitative comparison with theory.
- Theoretical predictions based on nuclear shadowing (EPS09 + NLO) are in fair agreement with the J/ψ and data. Similarly for models including also partonic energy loss.
- Same picture for Υ production.
- While models predict identical behavior for J/ψ and ψ(2s), the data shows differences.

  → hint at final state effects

  → unexpected, because charmonia formation time is larger than cc crossing time in the nucleus

  → Suppression due to interaction with the (hadronic) medium created in the collision?





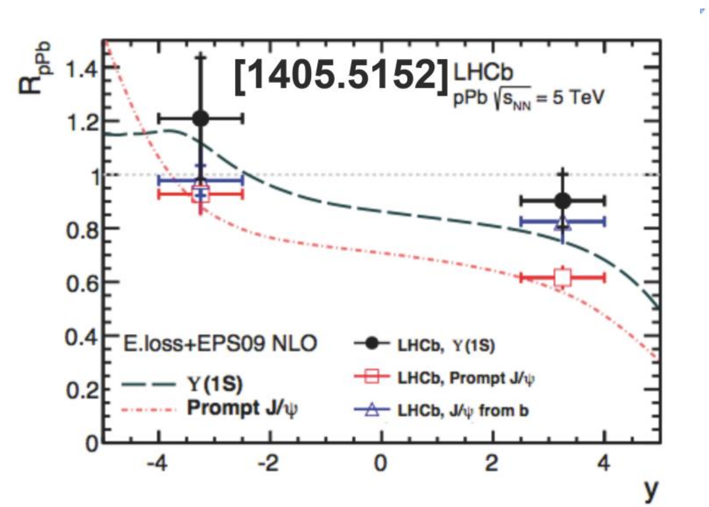
Quarkonia (1)

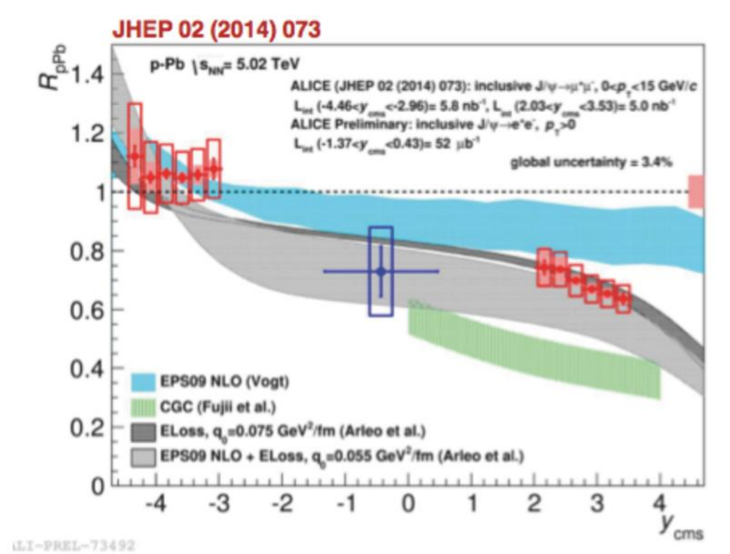
- In general, nuclear absorption effects are small at the LHC. Precision of the data allows for quantitative comparison with theory.
- Theoretical predictions based on nuclear shadowing (EPS09 + NLO) are in fair agreement with the J/ψ and data. Similarly for models including also partonic energy loss.
- Same picture for Υ production.
- While models predict identical behavior for J/ψ and ψ(2s), the data shows differences.

  → hint at final state effects

  → unexpected, because charmonia formation time is larger than cc crossing time in the nucleus

  → Suppression due to interaction with the (hadronic) medium created in the collision?





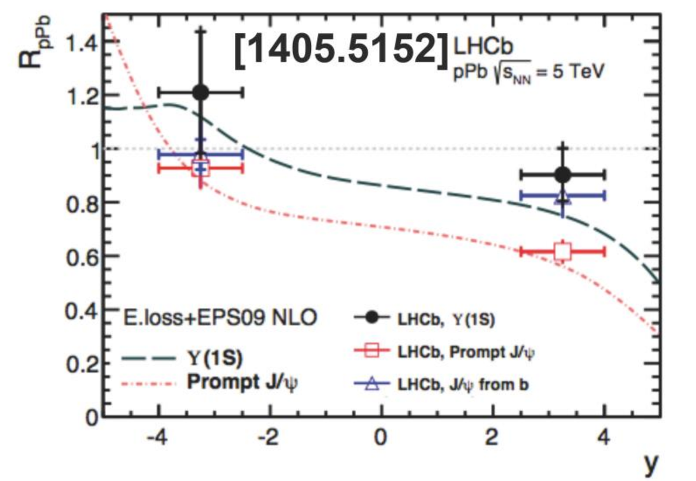
Quarkonia (1)

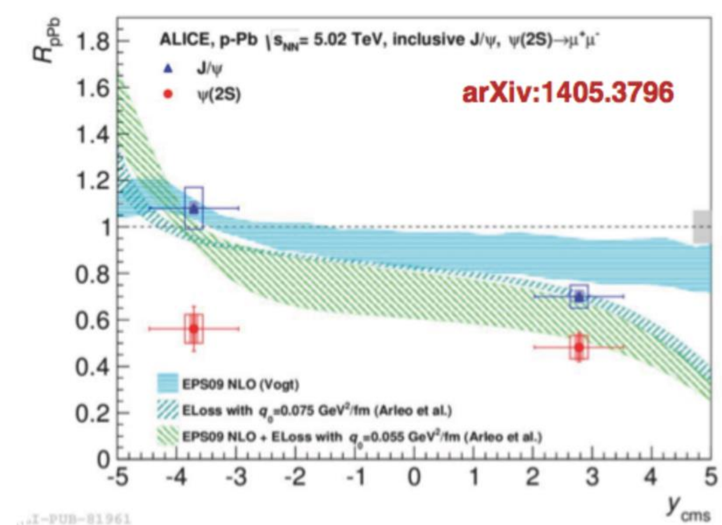
- In general, nuclear absorption effects are small at the LHC. Precision of the data allows for quantitative comparison with theory.
- Theoretical predictions based on nuclear shadowing (EPS09 + NLO) are in fair agreement with the J/ψ and data. Similarly for models including also partonic energy loss.
- Same picture for Υ production.
- While models predict identical behavior for J/ψ and ψ(2s), the data shows differences.

  → hint at final state effects

  → unexpected, because charmonia formation time is larger than cc crossing time in the nucleus

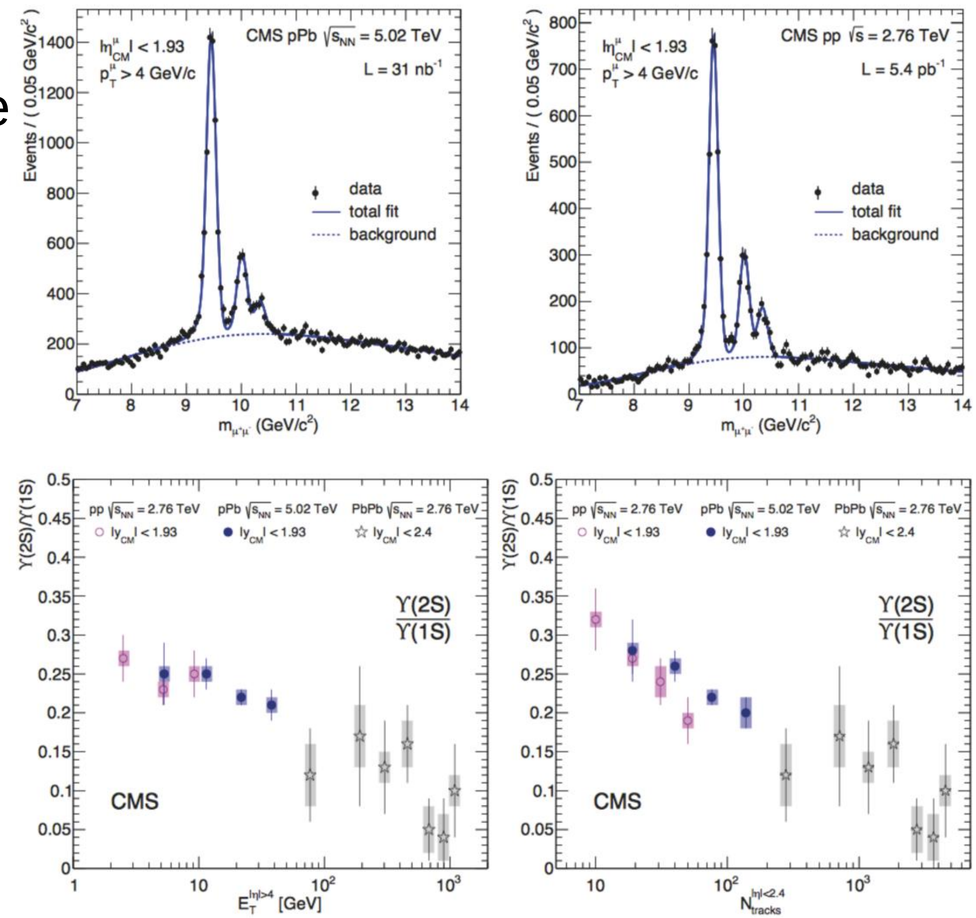
  → Suppression due to interaction with the (hadronic) medium created in the collision?





Quarkonia (2)

- Excited Υ states are less suppressed with respect to the ground states in min. bias p-Pb collisions than in Pb-Pb collisions.
- However, the suppression of excited states seems to vary with the event multiplicity (same in pp).
- It is an open question if excited states add multiplicity (event selection bias) or if the activity suppresses excited states (as in Pb-Pb collisions).

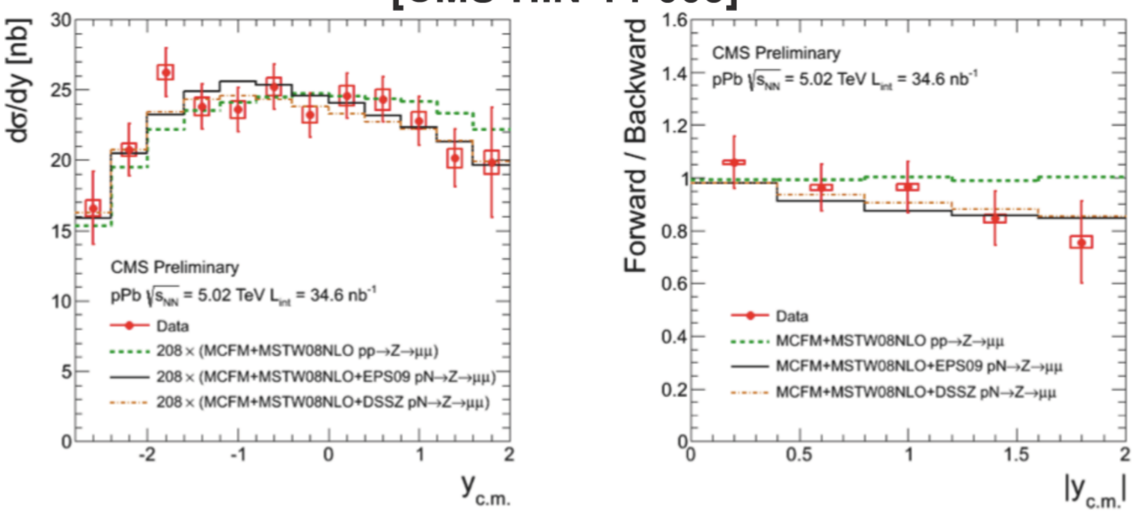


JHEP 04 (2014) 103

Z^0 production in p-Pb collisions

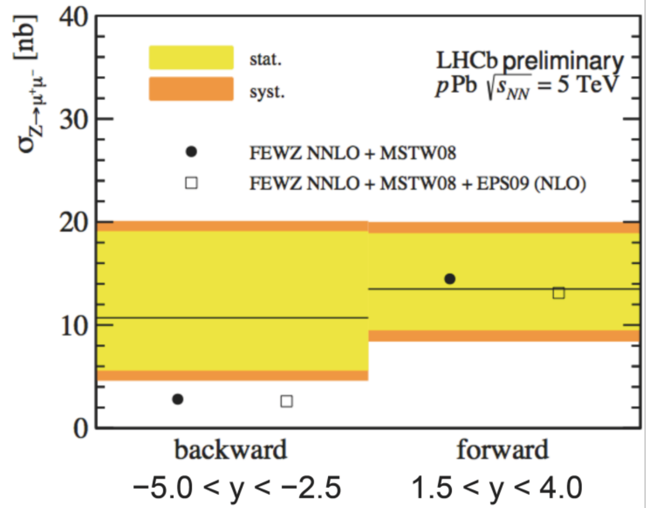
- New in the LHC energy regime… ≈ 2200 Z seen by CMS in $\mu^+\mu^-$ (similar for ATLAS). Also results from LHCb, but with much smaller statistics (≈ 15 candidates).
- Similar studies for W^+ and W^- (≈ 21000 $W\rightarrow\mu^+\nu$, ≈ 16000 $W\rightarrow e^+\nu$).
- Hints of forward-backward asymmetry might help to constrain nuclear PDFs

[CMS-HIN-14-003]



CMS

[LHCb-PAPER-2014-022]

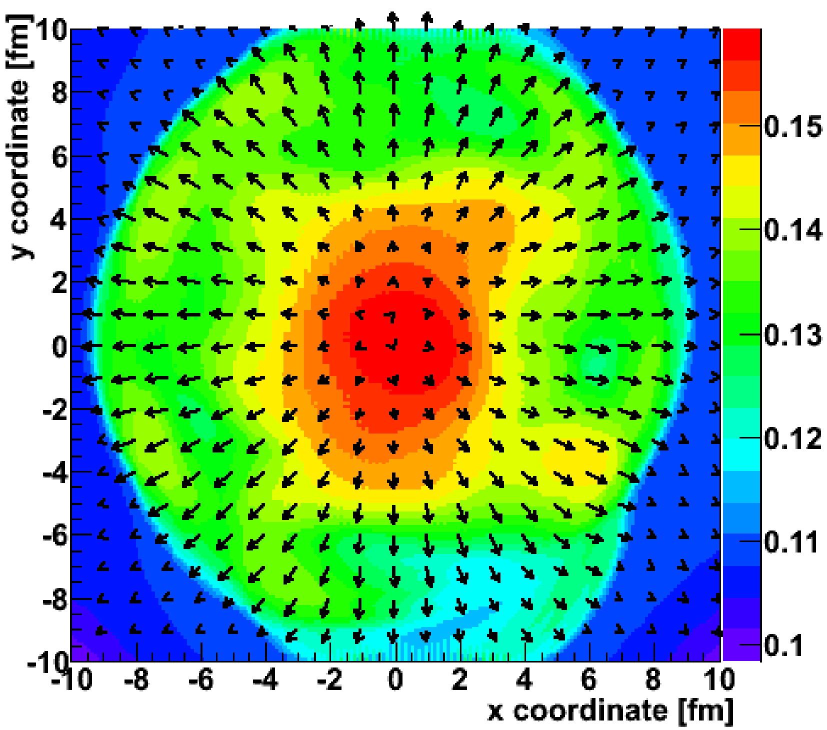


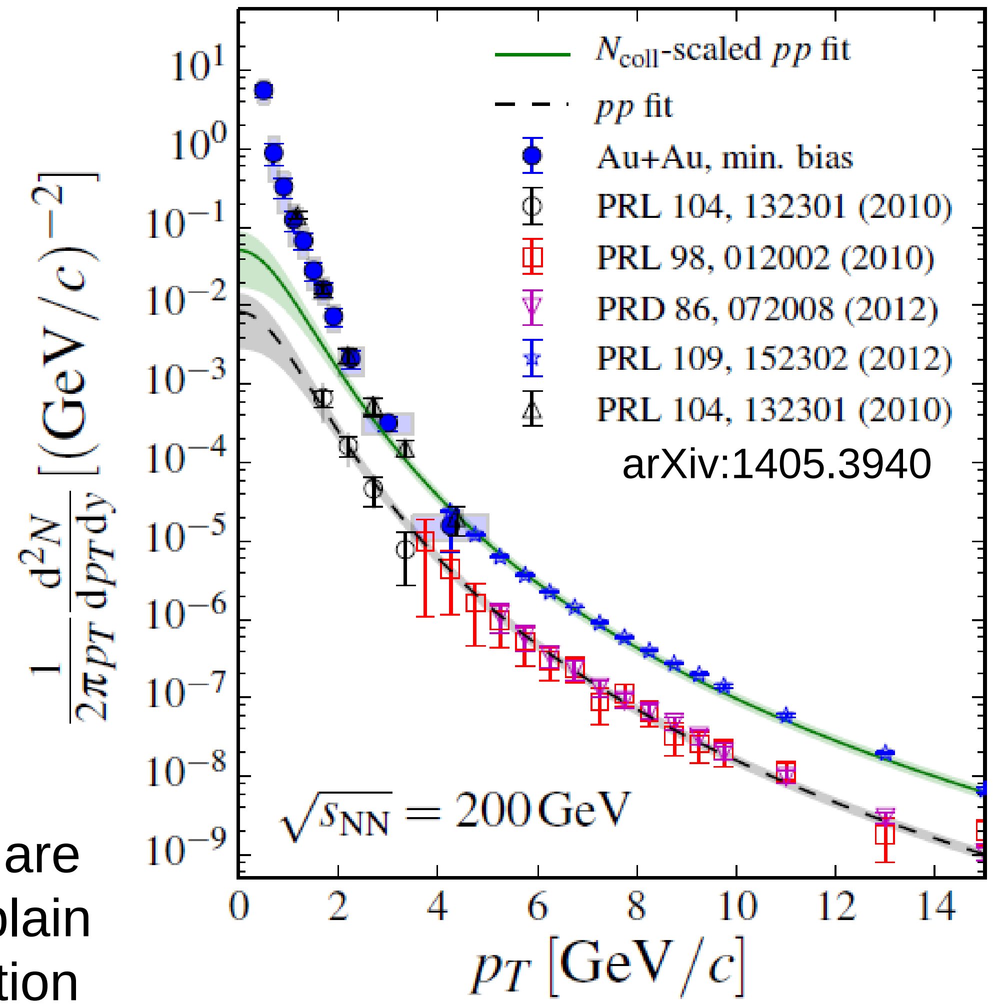
LHCb

PHENIX Direct Photons – QGP Shine

Photons emitted from high T fluid cells and Doppler blue shifted

Temperature Profile + Velocity Vectors

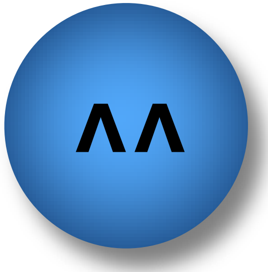




New spectra, v_2, v_3 of direct photons are a challenge for models of QGP to explain without stronger coupling near transition temperature

Search for exotic objects

Exotica - Introduction



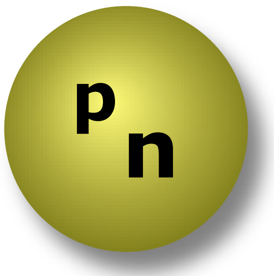
H-dibaryon (*uuddss*):

First predicted by Jaffe in a bag model calculation

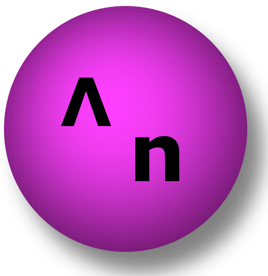
(Jaffe, PRL 38 (1977) 195)

Recent lattice calculations suggest bound state or a resonance close to the Ξp threshold

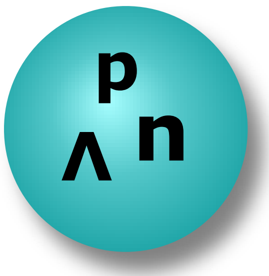
Λn bound state:



✔



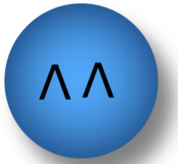
?



✔

H-dibaryon

Expected H-dibaryons ($H \rightarrow \Lambda p \pi^-$):



$$N_{H^0} = \underbrace{1.38 \cdot 10^7}_{\text{events}} \cdot \underbrace{0.0385}_{\text{eff.}} \cdot \underbrace{0.64}_{BR(\Lambda)} \cdot \underbrace{3.1 \cdot 10^{-3}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 2110$$

→ BR(H-dibaryon)

strongly bound H: 2110 · 0.1 = 211 lightly bound H: 2110 · 0.64 = 1350

H-dibaryon

Expected H-dibaryons ($H \rightarrow \Lambda p \pi^-$):

$$N_{H^0} = \underbrace{1.38 \cdot 10^7}_{\text{events}} \cdot \underbrace{0.0385}_{\text{eff.}} \cdot \underbrace{0.64}_{BR(\Lambda)} \cdot \underbrace{3.1 \cdot 10^{-3}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 2110$$

→ BR(H-dibaryon)

ΛΛ

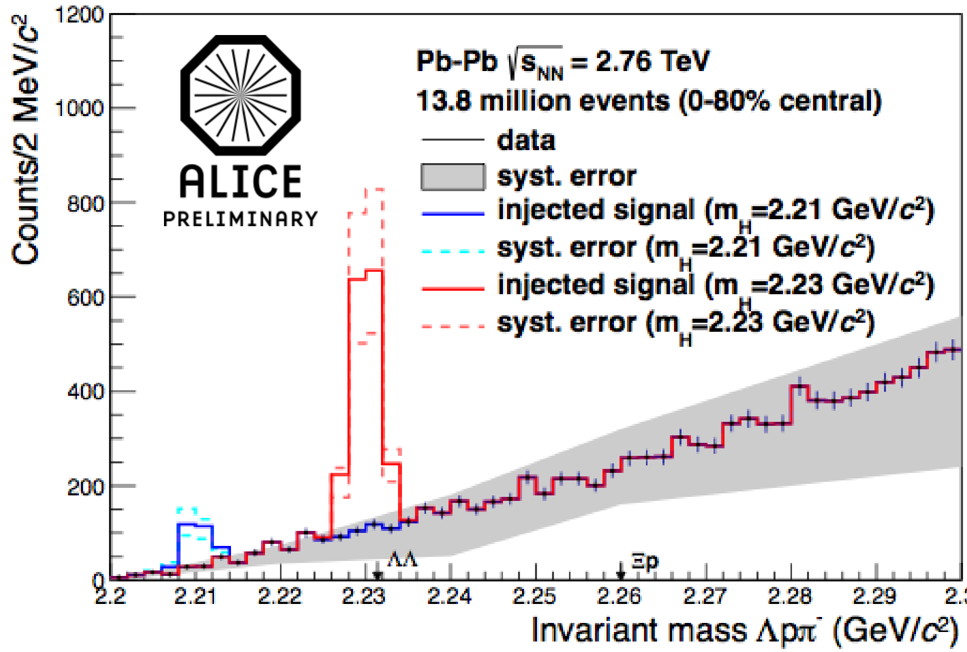
strongly bound H: $2110 \cdot 0.1 = 211$ lightly bound H: $2110 \cdot 0.64 = 1350$

No signal visible

From the non-observation we obtain as **upper limits**:

For a strongly bound (20 MeV) H:
➜ $dN/dy \leq 8.4 \cdot 10^{-4}$ (99% CL)

For a lightly bound (1 MeV) H:
➜ $dN/dy \leq 2 \cdot 10^{-4}$ (99% CL)



$\overline{\Lambda}\overline{n}$ bound state

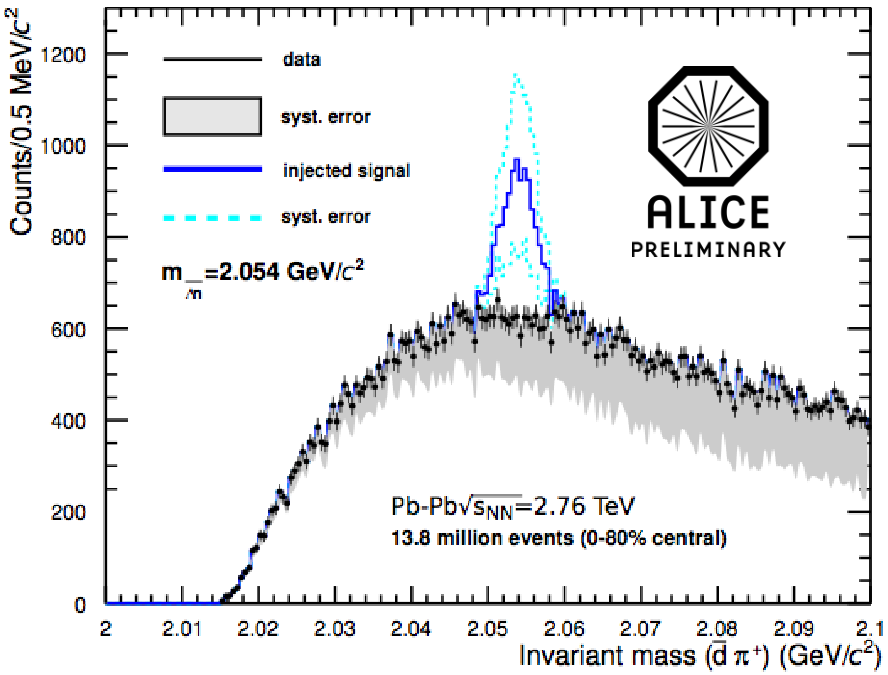
Expected $\overline{\Lambda}\overline{n}$ bound states ($\overline{\Lambda}\overline{n} \rightarrow \overline{d}\pi^+$):

$$N_{\overline{\Lambda}\overline{n}} = \underbrace{1.38 \cdot 10^7}_{\text{events}} \cdot \underbrace{0.0255}_{\text{eff.}} \cdot \underbrace{0.35}_{\text{BR}} \cdot \underbrace{1.6 \cdot 10^{-2}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 4000$$

No signal visible

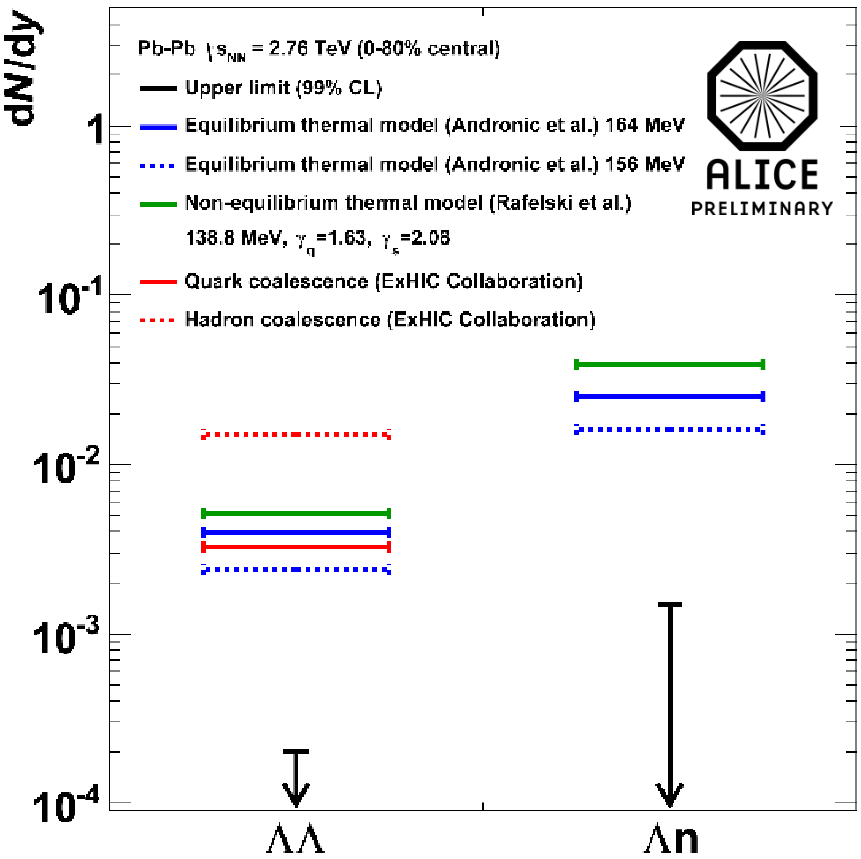
From the non-observation we obtain as **upper limit**:

➜ $dN/dy \leq 1.5 \cdot 10^{-3}$ (99% CL)



Comparison to models

- The $\overline{\Lambda n}$ bound state and the H-dibaryon are not observed
- Different model predictions are of the same order
- Upper limits for the two particles are set, at least a factor 10 below model predictions

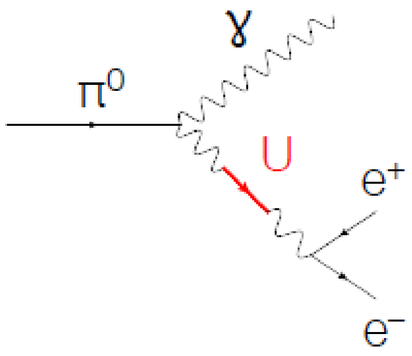


→ Existence of these particles with the assumed properties (BR, mass, lifetime) is questionable

Dark Photon Search

Muon g-2 experiment (E821) has 3.6σ result beyond the Standard Model

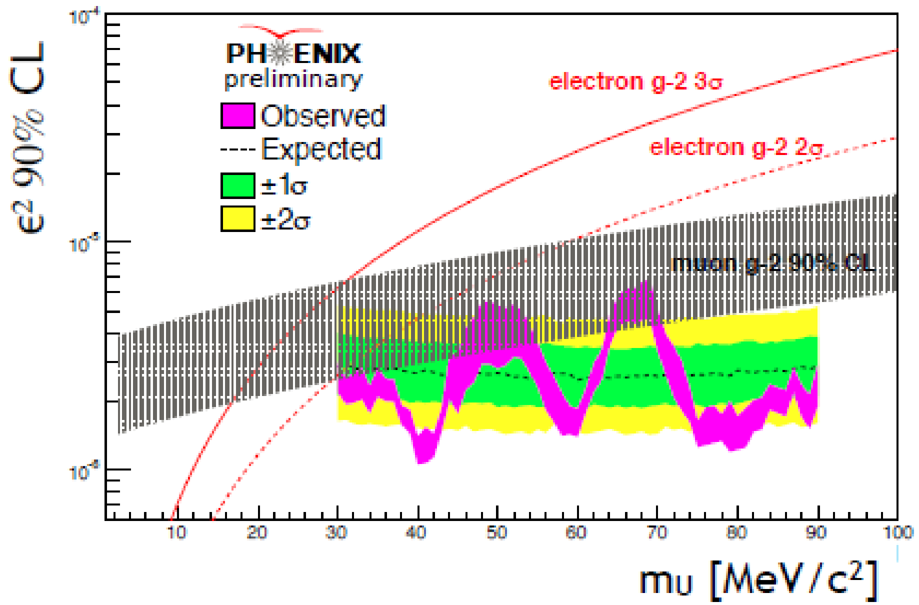
One explanation is the dark photon – Low mass, weak coupling



PHENIX, HADES and ALICE have excellent dark photon search capabilities

No dark photon signal seen

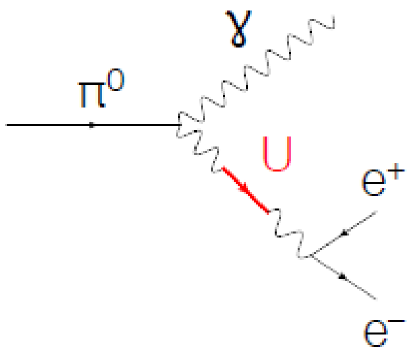
Our upper limit, plus others, nearly rules out dark Photons as g-2 explanation



Dark Photon Search

Muon g-2 experiment (E821) has 3.6σ result beyond the Standard Model

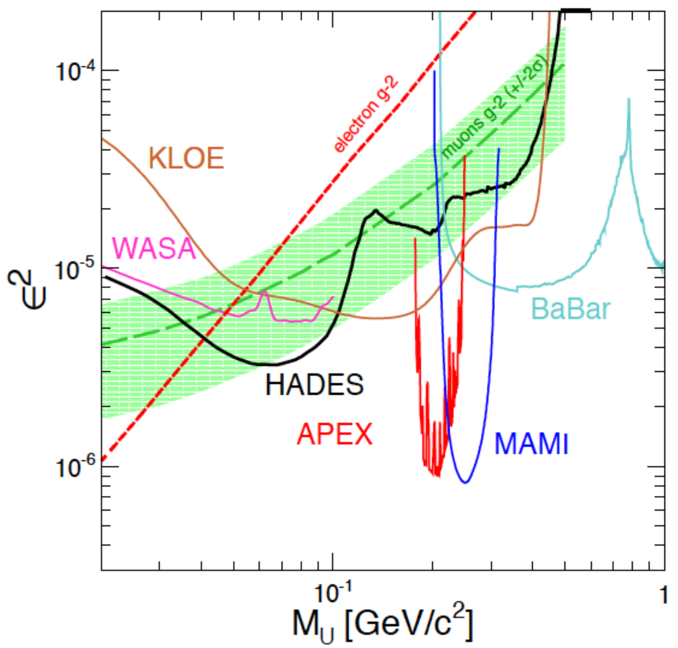
One explanation is the dark photon – Low mass, weak coupling



PHENIX, HADES and ALICE have excellent dark photon search capabilities

No dark photon signal seen

Our upper limit, plus others, nearly rules out dark Photons as g-2 explanation

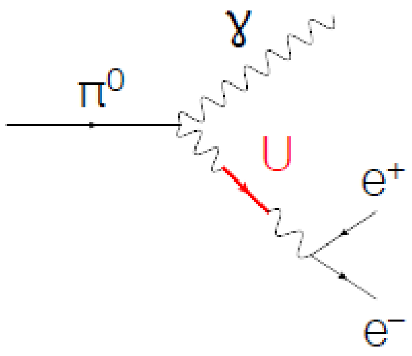


G. Agakishiev et al., Phys. Lett. B 731 (2014) 265

Dark Photon Search

Muon g-2 experiment (E821) has 3.6σ result beyond the Standard Model

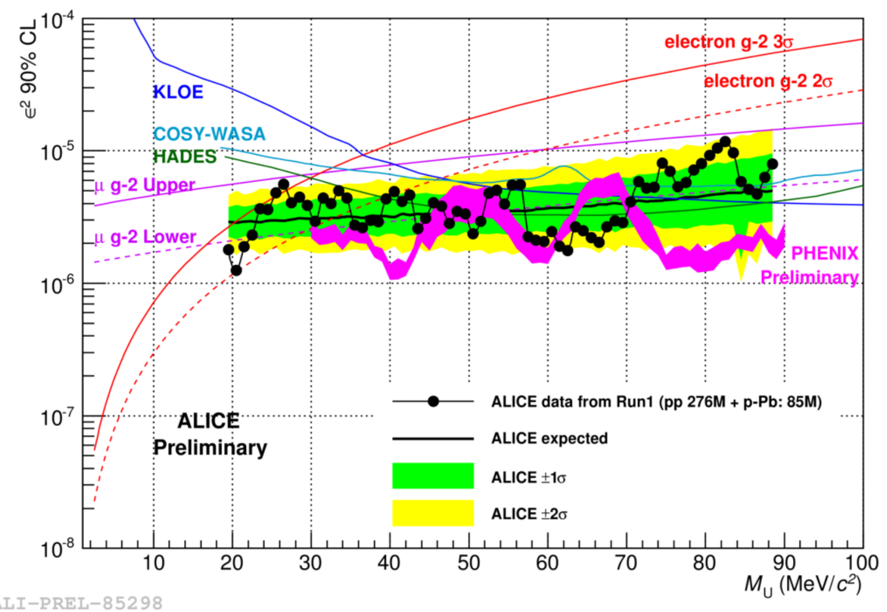
One explanation is the dark photon – Low mass, weak coupling



PHENIX, HADES and ALICE have excellent dark photon search capabilities

No dark photon signal seen

Our upper limit, plus others, nearly rules out dark Photons as g-2 explanation



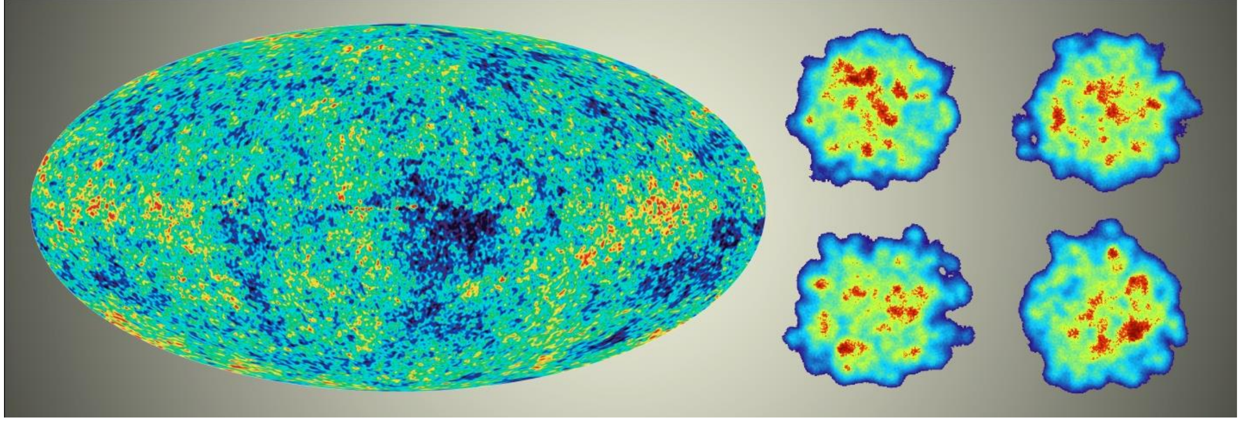
Summary and conclusion

Summary and Conclusion

- A lot of interesting physics results from A-A and in particular p/d-A
- Pb-Pb/Au-Au like features are observed for the bulk of the produced particles at low p_T: v_2, radial flow, thermal fits..
- No indications of *quenching* at high p_T (charged hadrons, jets, open charm, heavy flavor, electrons, muons). However, CMS & ATLAS observe a yet unexplained *enhancement* at high p_T…
- Quarkonia measurements provide an essential baseline for the understanding of the Pb-Pb results. Electroweak bosons can help to constrain nPDFs and centrality estimators.
- For searches of exotic objects significant upper limits have been set
- Very interesting times ahead of us…

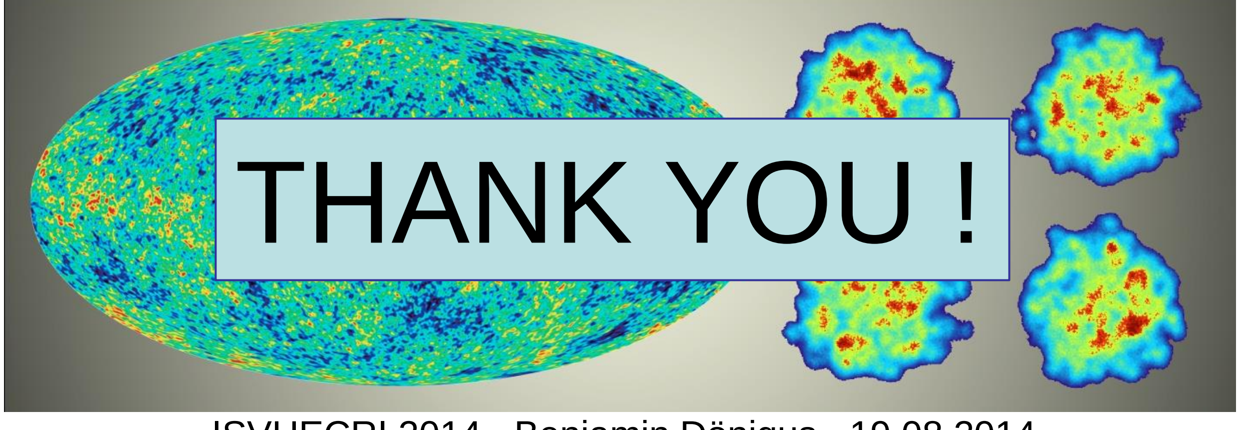
Summary and Conclusion

- A lot of interesting physics results from A-A and in particular p/d-A
- Pb-Pb/Au-Au like features are observed for the bulk of the produced particles at low p_T: v_2, radial flow, thermal fits..
- No indications of *quenching* at high p_T (charged hadrons, jets, open charm, heavy flavor, electrons, muons). However, CMS & ATLAS observe a yet unexplained *enhancement* at high p_T…
- Quarkonia measurements provide an essential baseline for the understanding of the Pb-Pb results. Electroweak bosons can help to constrain nPDFs and centrality estimators.
- For searches of exotic objects significant upper limits have been set
- Very interesting times ahead of us…



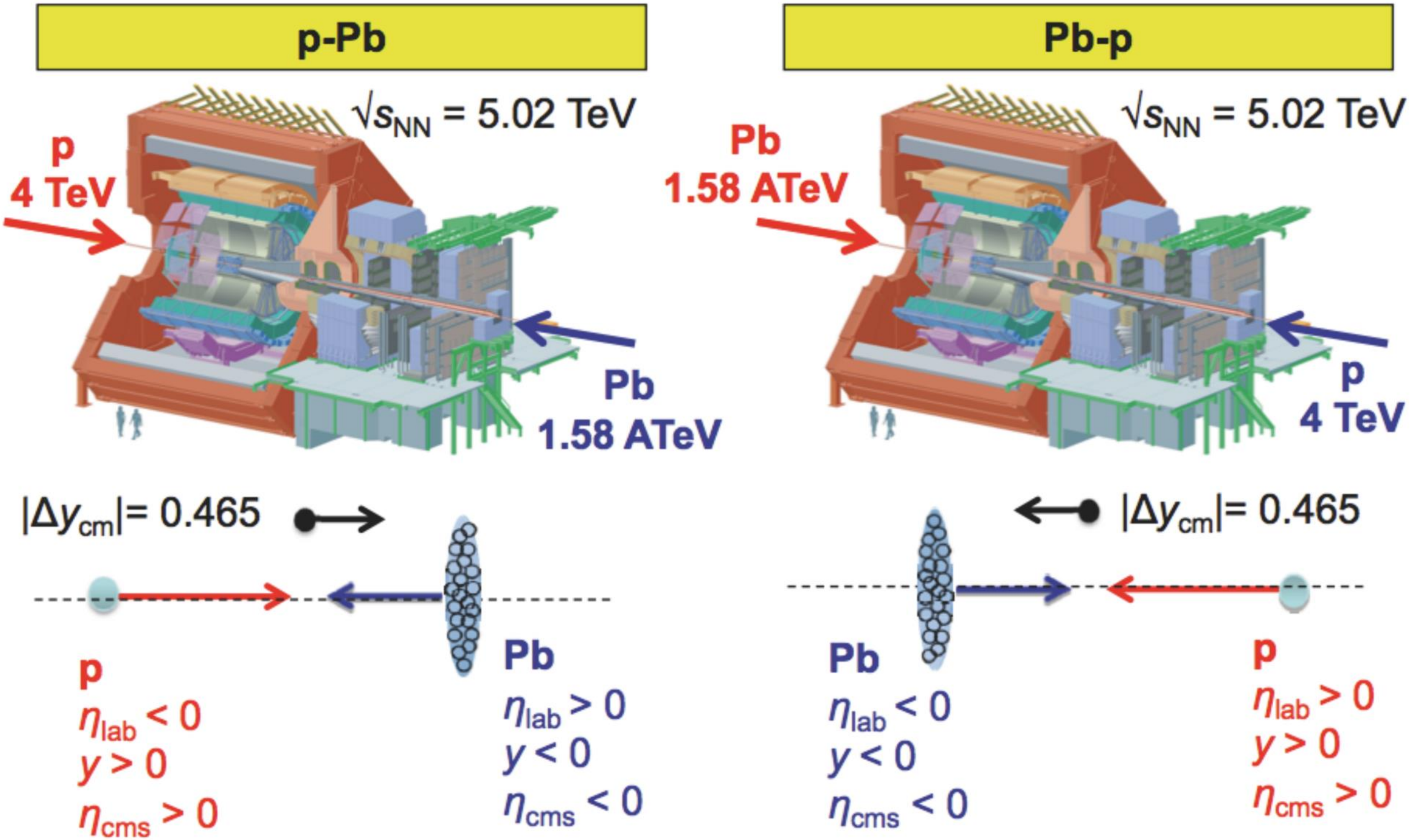
Summary and Conclusion

- A lot of interesting physics results from A-A and in particular p/d-A
- Pb-Pb/Au-Au like features are observed for the bulk of the produced particles at low p_T: v_2, radial flow, thermal fits..
- No indications of *quenching* at high p_T (charged hadrons, jets, open charm, heavy flavor, electrons, muons). However, CMS & ATLAS observe a yet unexplained *enhancement* at high p_T…
- Quarkonia measurements provide an essential baseline for the understanding of the Pb-Pb results. Electroweak bosons can help to constrain nPDFs and centrality estimators.
- For searches of exotic objects significant upper limits have been set
- Very interesting times ahead of us…



BACKUP

p-Pb collision geometry



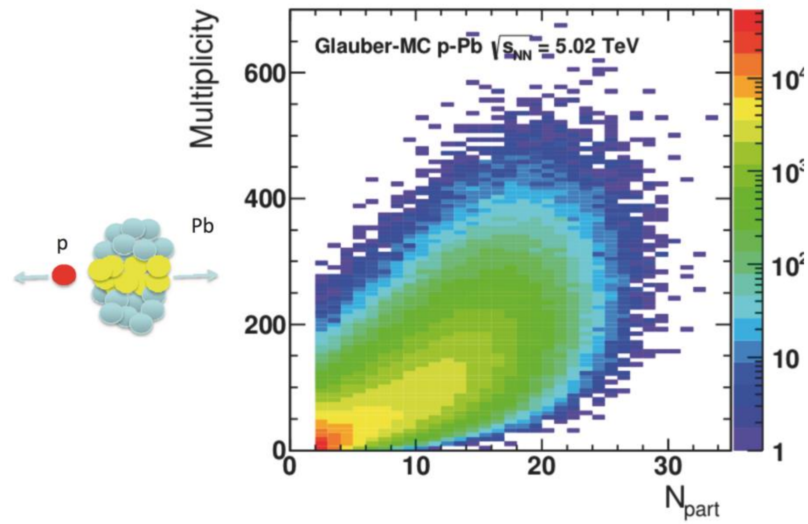
the direction fo the proton is always at positive $y \equiv y_{cms}$ and positive η_{cms}

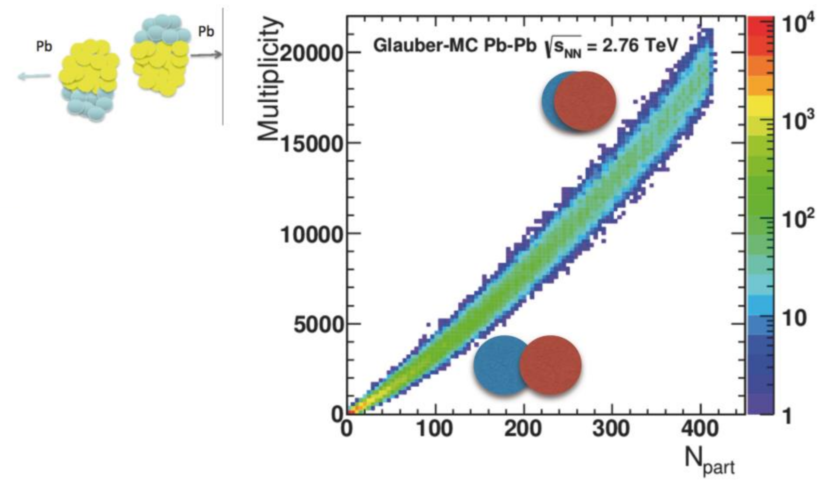
Centrality — Introduction

- In contrast to Pb-Pb collisions, it is not straightforward to relate experimental quantities to the collision geometry, i.e. the number of participants N_{part} and binary collisions N_{coll}.

  → in p-Pb collisions: $N_{coll} = N_{part} - 1$
- Large biases present in the system:
  - Multiplicity fluctuations
  - Jet-veto bias
  - Geometric bias

• Most simple approach: only multiplicity classes instead of centrality, but more can be done…





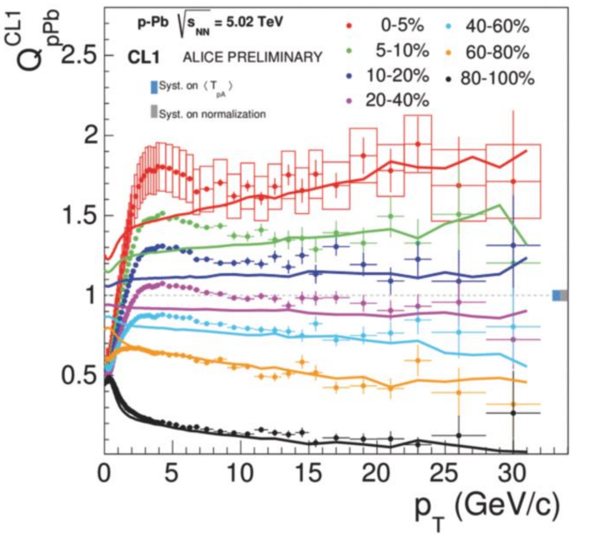
Different experiments employ different approaches in order to deal with biases.
One needs to be careful in comparisons.

Centrality — ALICE

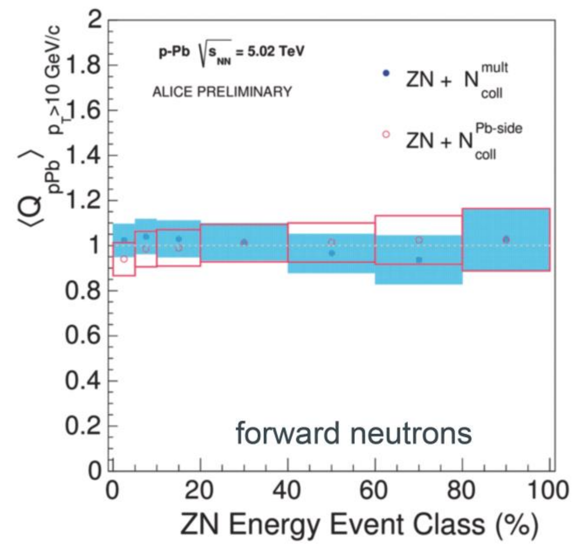
- Standard Glauber fit+event selection (a la AA) leads to results which depends on the η-region of the centrality estimator.
- Example Q_{pA} (not called R_{pA}, because collision geometry is not properly reflected):

$$Q^{i}_{pA} = \frac{dN_{pA}/dp_T}{\langle N_{coll} \rangle_i \, dN_{pp}/dp_T}$$

Standard Glauber fit+event selection

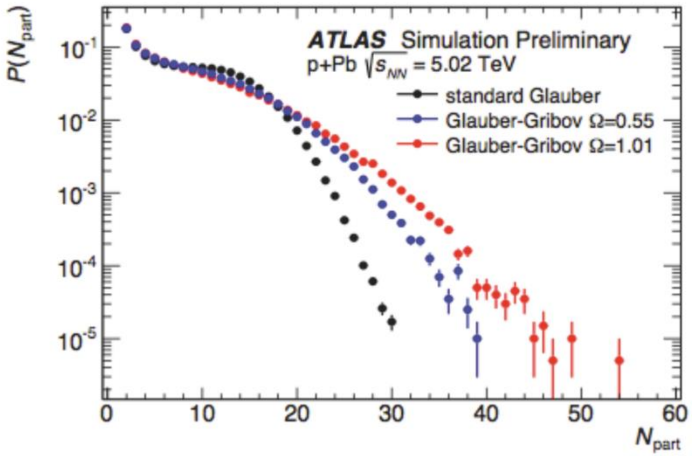


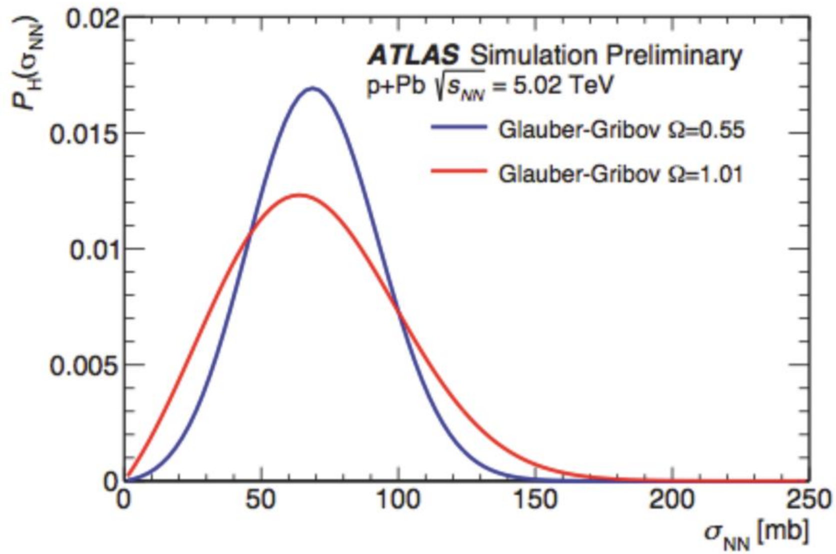
- Forward neutrons (measured in Zero Degree calorimeter) cause no selection bias on mid-rapidity
bulk production
-> used to bin events in classes
- Determine N_{coll}/N_{part} by assuming one out of:
  - Mid-rapidity dNch/dη ~ Npart
  - Forward dNch/dη ~ $N^{Pb}_{part} = N_{part} - 1$
  - High p_T yield ~ N_{coll}
- Methods reach consistent results:
  - N_{coll} consistent within 5-10%
  - High p_T Q_{pA} flat (> 10GeV/c)

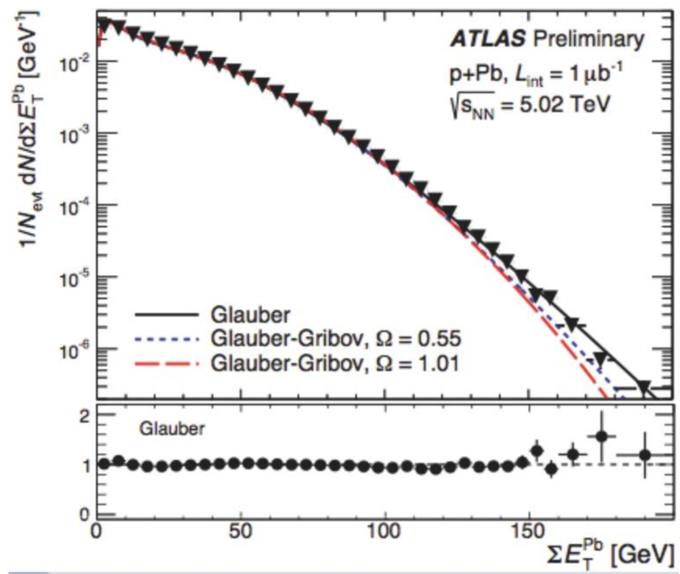


Centrality — ATLAS

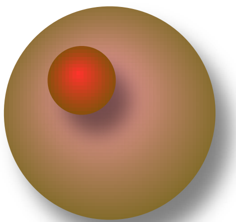
- A different approach is used:
  - The underlying model is changed from a Glauber model to a Glauber-Gribov.
- NN cross-section is subject to quantum fluctuations in the proton configuration (controlled by fluctuation parameter Ω).
- Model can be constrained by pp diffraction data.



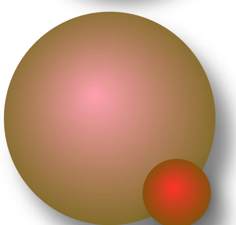




multiplicity classes in p-Pb



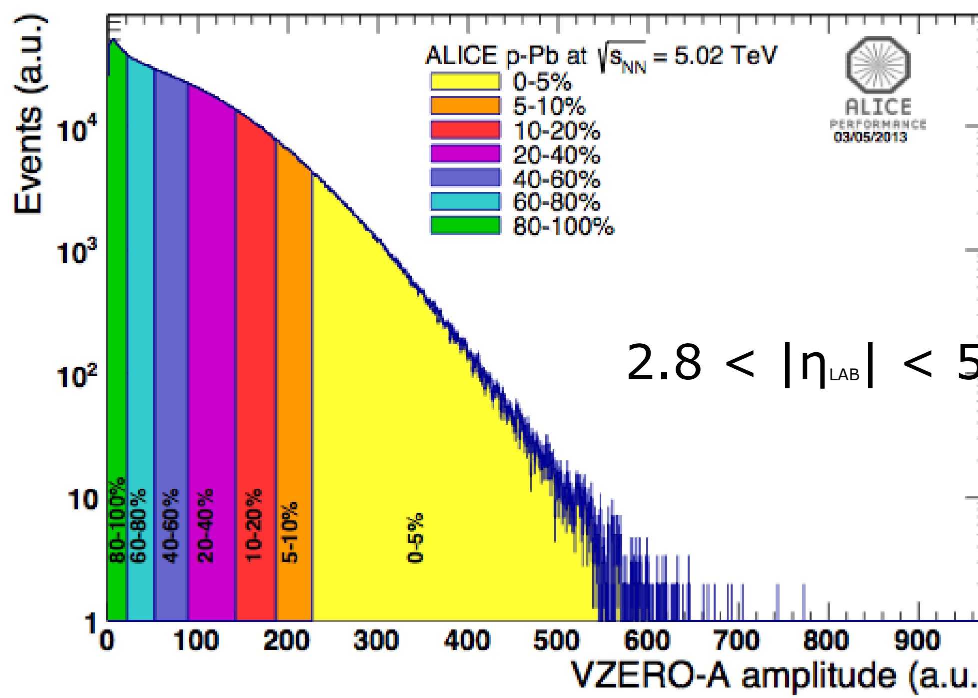
central



peripheral

Correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb

Definition of seven multiplicity classes:
➜ slices in VZERO-A (V0A) amplitude



$2.8 < |\eta_{LAB}| < 5.1$